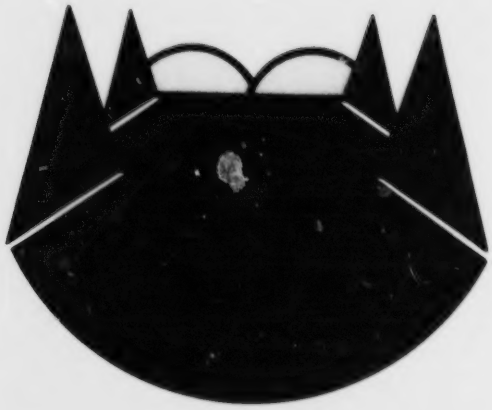

Earth Sciences Report 82-2

## Groundwater Hydrology of the

# Pine Lake Research Basin, Alberta

### A Preliminary Analysis

by G. Garven

Alberta
RESEARCH COUNCIL

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**Alberta Research Council**
**1982**

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## ABSTRACT

The Pine Lake research basin is a 230 km² (90 sq mi) parkland in south-central Alberta. Various types of geologic, geophysical, and hydrologic data were used to evaluate the hydrogeology of the research basin.

Permeable sandstone, mudstone, and coals of the thick Paskapoo Formation underlie the study area. The major, shallow sandstone aquifers have hydraulic conductivities between 0.5 to 2.5 m/day (10 to 50 igpd/ft²). A thin mantle of glacial drift characterizes the surficial geology.

The water-table configuration is a subdued replica of the topography. Groundwater flows from broad recharge areas on the main divides to discharge areas in the valley bottom. Sodium-bicarbonate groundwater, which dominates the basin, evolved primarily through carbonate dissolution and cation exchange processes. Correlation between hydrochemical facies and groundwater flow patterns is poor. The groundwater regime in the research basin is most appropriately treated as a steady-state, regionally unconfined system in a heterogeneous and anisotropic rock medium. Natural basin yield was calculated from a finite-element simulation as 55 m³/day/m (4000 igpd/ft).

This analysis is designed as a framework for instrumentation and a guide for future hydrologic studies in the Pine Lake area. Recommendations for instrumentation and future studies include installation of a piezometer network, further aquifer testing and numerical modelling of saturated-unsaturated groundwater flow and hydrochemistry.


## INTRODUCTION

The Alberta Research Council's Groundwater Department planned for the establishment of an experimental research basin several years ago. The Pine Lake area in the south-central part of the province was recently chosen for this purpose, largely because of its good access, varied hydrogeologic conditions, and the potential of practical application of study results to the local area.

Tóth (1977) described the main purposes of the Pine Lake research basin as follows: (1) to investigate and measure subsurface components of the hydrologic cycle in a parkland environment; (2) to develop standard, or improved, methods of evaluating subsurface hydrologic parameters; and (3) to establish a research and training area where test results can be accumulated over a substantial period of time.

The objective of this report is to evaluate the groundwater hydrology of the proposed Pine Lake research basin. This study is based solely on field reconnaissance observations, existing subsurface data, and the results of a small exploration program. The report will develop a framework for future instrumentation of the basin and detailed analysis.


## ACKNOWLEDGMENTS

A major portion of the data was collected while the author was employed as a research officer (summers of 1978, 1979) with the Groundwater Department of the Alberta Research Council. Much of the analysis and interpretation was performed in the interim period at the University of Arizona where the author was a graduate student. The author is grateful for the research and field experience as well as for the permission of the Research Council to use department-generated data as a basis for a master's thesis (Garven, 1980).

The author would also like to thank the staff of the Groundwater Department whose assistance, directly or indirectly, aided the Pine Lake research

basin project. J. Tóth supervised the work, gave invaluable advice, and provided discussion on the significance of field mapping groundwater phenomena in hydrologic investigations. E.J. Wallick offered enlightening discussions on the hydrogeology and hydrochemistry of the Pine Lake area. G.M. Gabert's assistance was sincerely appreciated and W. Ceroici extended much help on the project.

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D.W. Organ of Chevron Standard Limited supplied structure testhole electric logs for the entire study area. R. Rahmani of Coal Geology, Alberta Research Council, supplied logs for a number of testholes in the Pine Lake area. Their special contribution is gratefully acknowledged.

Testhole drilling was most competently handled through Lousana Water Wells Ltd., Lousana, Alberta. The author would also like to express his sincere thanks to the staff of the Groundwater Department who aided the field projects, in particular G. Sjostrom and A. Beerwald. Cooperation of the residents in the Pine Lake area facilitated the field mapping and exploration programs.

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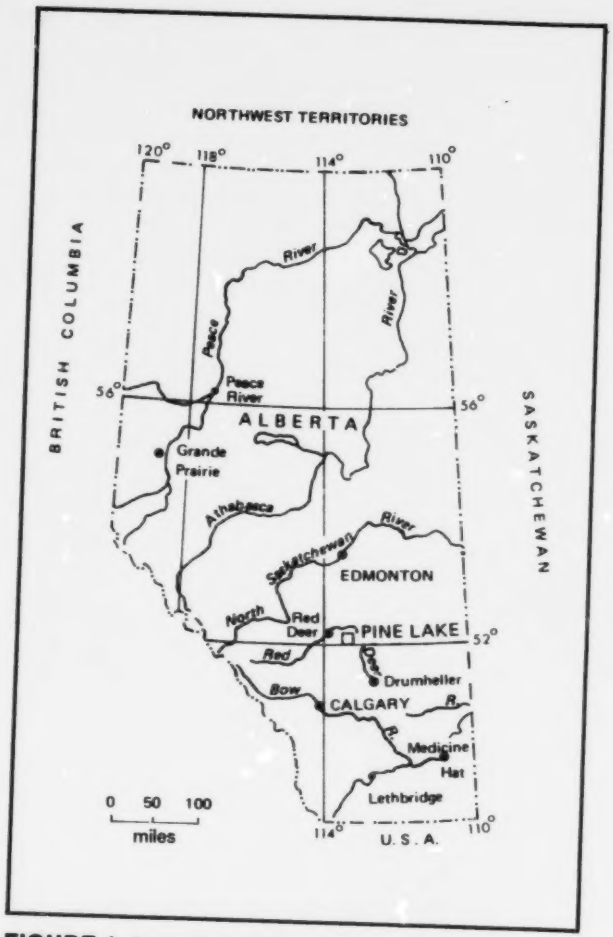


**FIGURE 1.** Location of Pine Lake, Alberta.

## LOCATION AND EXTENT OF STUDY AREA

Pine Lake is located in what is described as the Western Alberta Plains, in south-central Alberta, as shown in figure 1. It is approximately 125 km (80 mi) north-northeast of Calgary.

The research basin, itself, is about 230 km² (90 sq mi) of the upper portion of the Ghostpine Creek drainage basin, as shown in figure 2. It lies within the area of townships 35 to 37, and ranges 24 to 26, west of the fourth meridian, between 113°17′ and 113°43′ west longitude, and 51°58′ and 52°14′ north latitude. The southern boundary of the basin is partially arbitrary.

## PREVIOUS WORK

Several groundwater resource surveys have been conducted in south-central Alberta, but the Pine Lake area has not previously undergone detailed hydrogeological investigation. Early studies that partly included the Pine Lake basin were those of Latour (1947) and Stalker (1950), of the Geological Survey of Canada. They described geology and groundwater resources for each township in the

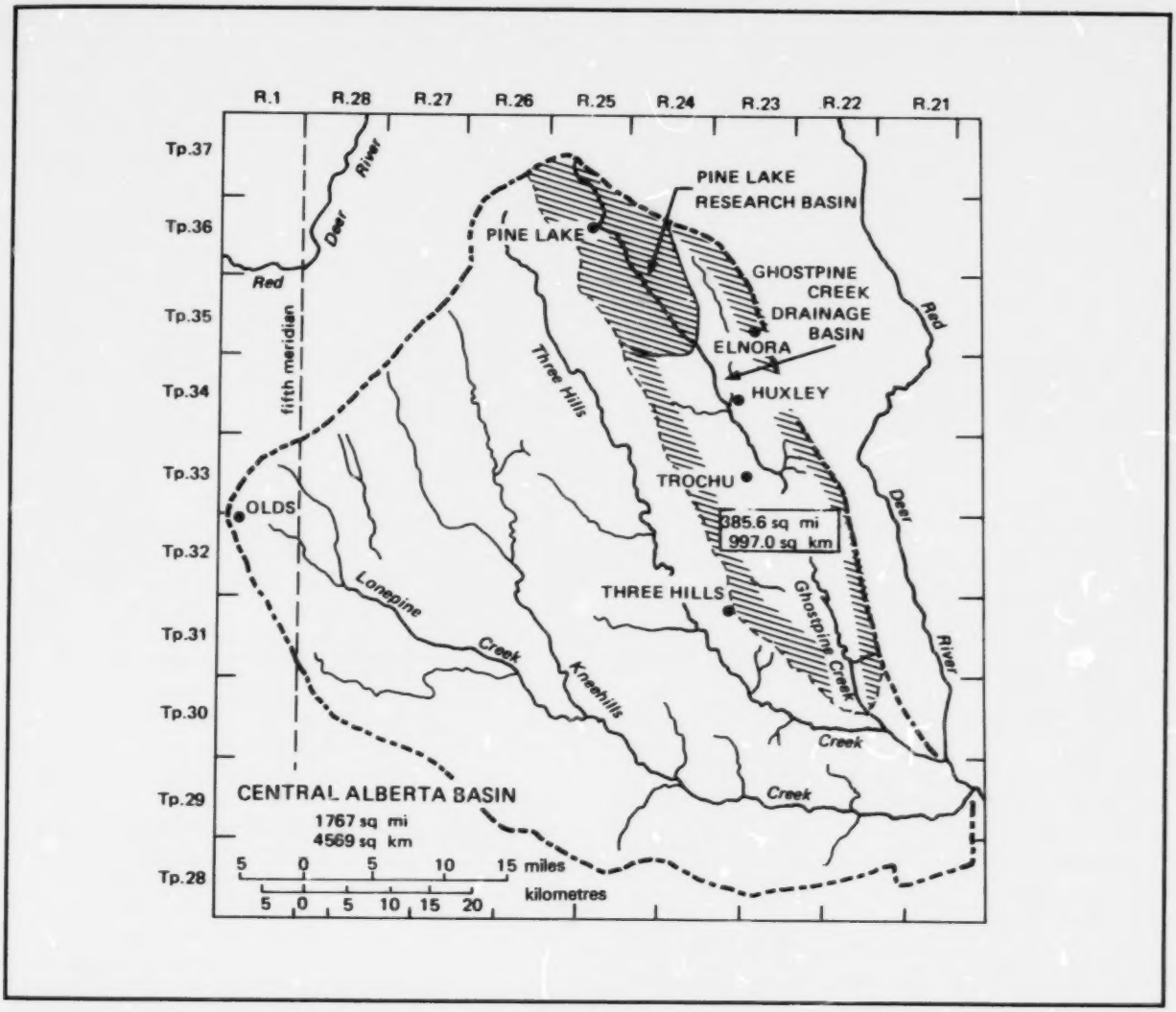


**FIGURE 2.** Map of central Alberta showing regional drainage and location of the Pine Lake research basin.

respective map areas, using a well-inventory approach. Maps showing surficial geology and topography, with location of wells, were published at a scale of 1 inch to 3 miles. Basic data consisted of well records and yields, aquifer types, use, and water quality. The information from these reports has been of great value to the present study.

The Alberta Research Council has published the most recent analysis of the regional groundwater resources. Le Breton (1971) and Borneuf (1972) completed studies on the reconnaissance hydrogeology of the Red Deer and Drumheller map sheets, respectively. Maps published by these authors are on a scale of 1:250 000 and cover about 13 000 km² (5000 sq mi). The maps, and several regional cross sections, illustrate the generalized geology to a depth of about 300 m (1000 ft), direction of groundwater flow, subsurface hydrogeologic properties, groundwater probability, hydrochemistry, locations of springs, and flowing wells, and relevant meteorological data. The Pine Lake research basin comprises a

small part of the total area investigated by Le Breton (1971). Furthermore, only a very small portion is in the area mapped by Borneuf (1972).

There are detailed groundwater studies of areas adjacent to the Pine Lake basin, where similar hydrogeological conditions exist. Tóth (1966a) mapped and interpreted groundwater phenomena in a section of the Ghostpine Creek Valley near Trochu (see fig. 2), southeast of the Pine Lake research basin. Tóth (1968) also made an extensive investigation of the Three Hills area, which included a portion of the Ghostpine Creek drainage basin, downstream of the 1966 study. Gabert (1975) made an extensive study of the hydrogeology of the Red Deer area. The southeast corner of Gabert's map area partially overlaps the northwestern region of the Pine Lake study area. The interpretations made by these authors, and their methods of analysis, have been invaluable to the present study.

## TYPE, SOURCE, AND TREATMENT OF DATA

The location and types of basic data used in the present study are shown in figures 3, 4 and 5. The location map of general well data (fig. 3) represents all existing geologic and hydrologic information on the Pine Lake research basin available in the files of the Groundwater Data Center, Alberta Research Council. Many well records published by Latour (1947) are represented on this map.

Most well data shown (fig. 3) come from reports submitted by water well drillers over the past 15 to 20 years. These records describe well construction, details of completion, static water levels, lithologies, and recovery measurements of water levels after a brief bail test. Time-drawdown data from pump or bail tests are rare. Water chemistry analysis of samples submitted to rural health authorities by private well owners are numerous. The major anions and cations are usually reported, along with total dissolved solids, hardness, alkalinity, conductivity, fluorides, and iron. Other information obtained from the data center files included reports of water levels and details of well construction from well inventory surveys, seismic shothole reports from exploration companies, and a few electric logs from oil or gas wildcat wells. Records were also available on three observation wells, equipped with continuous water level recorders. Groundwater hydrographs are available from 1963 to the present. Considerable time and effort was devoted to interpreting all well records and the results are summarized in appendix A. Appendix B is a schedule listing water chemistry analyses. Pertinent data for any given well location on the map can be found listed under its index number in either schedule.

A second major type of data used in the Pine Lake study consisted of observations and chemical analyses of water samples obtained during the field survey in the summer of 1978. Figure 4 illustrates the type and distribution of field observations. Descriptions of these features were recorded in a set of field notes. Water samples from wells, springs, and surface water were collected throughout the research basin. The results of the chemical analyses of these samples are listed with the earlier data in appendix B.

The third major source of data used to evaluate the Pine Lake area were logs of deep wells (fig. 5), usually drilled for reasons other than for water supply. Structure testhole electric logs are a large portion of the deep geologic information for the Pine Lake basin. These testholes were drilled in the early 1950s to obtain shallow structural-stratigraphic data that would indicate potential oil-or-gas-producing formations at much greater depths. Chevron Standard Ltd. and the Energy Resources Conservation Board, both of Calgary, provided electric self-potential and resistance logs for testholes. Figure 5 also shows the locations of testholes drilled for a coal study by the Alberta Research Council. A lithological log and various types of geophysical logs were available for these holes. Also on this map are locations of oil or gas wildcat wells for which geophysical logs are available. Unfortunately, these logs are of little value to this study because the logging usually stopped at a depth of around 200 to 250 m (600 to 800 ft), depending on the length of the surface casing. Occasionally, a radioactivity-type log can be used for shallow stratigraphic interpretation.

Elevations of water wells were estimated from a topographic base map with 25-ft contours. Ground elevations of seismic shotholes, structure testholes, and oil or gas wildcat wells reported on the logs are presumed to have been surveyed. The only other hydrogeologic data generated by this preliminary study consists of the test drilling and aquifer testing at four sites in the research basin.

## GEOGRAPHIC CONSIDERATIONS

### TOPOGRAPHY

The Pine Lake research basin is located within a regional series of elongate ridges and valleys trending northwest-southeast in a portion of the Western Alberta Plains physiographic region (fig. 2). By far the most prominent regional topographic feature is the incised valley of the Red Deer River, which in places is over 150 m (500 ft) deep. Bedrock geology and differential erosion are responsible for the major topographic features in this region. The Pleistocene glaciations created many small, local features and modified the original topography of the bedrock. Figure 6 shows the topography and physiographic features of the Pine Lake basin. Elevations in the research basin range from over 1050 m (3450 ft) in the rugged ridge area at the northwest end, to less than 850 m (2850 ft) where Ghostpine Creek leaves the study area in the southeast.

### DRAINAGE

Compared to other parts of the Canadian prairie, regional drainage in south-central Alberta (fig. 2) is relatively good. Several authors have noted the marked parallelism and regular spacing of the four main creeks — Lonepine, Kneehills, Threehills, and Ghostpine. Tóth (1962, 1968) summarized the general characteristics of these creeks as shallow, underfit, meandering streams of a barely perennial nature whose discharge is quite variable.

The surface water drainage divide was used to define the boundary of the Pine Lake basin. This boundary was especially difficult to determine in hummocky areas and, furthermore, the research basin is not hydrologically closed because the southern boundary is not a surface drainage divide in the true sense. The southern boundary lies in a convenient location to limit the size of the research area.

Pine Lake is the only major surface water body in the Ghostpine Creek drainage basin (fig. 7). Two streams drain the northern part of the basin above Pine Lake. They do not directly drain the highly elevated region, but rather their head waters are located along the margin of hummocky areas. A subdued ridge, extending from the northern uplands, acts as a drainage divide between these streams down to their confluence near Pine Lake. Stream channels also drain broad areas of boggy lowland on both sides of the lake. In turn, Pine Lake is the reservoir for Ghostpine Creek. The creek meanders as an underfit stream with its bed incised into a wider preglacial valley. Tributaries to Ghostpine Creek have eroded significant drainage channels back into the main ridges. Several ponds and small lakes are found along the creek valley and some of its tributaries.

### SOILS

The Pine Lake basin lies almost entirely within the Black Soil zone of Alberta. Detailed descriptions of soil types can be found in the report by Bowser, Peters, Newton (1951), and need not be repeated here. For the most part, soils in this area are well-drained. Salt-affected profiles were only observed in the southern part of the basin, along Ghostpine Creek. Strong correlation between soil texture and glacial geology exists throughout the research basin.

### VEGETATION

Originally, the Pine Lake area was completely covered by typical parkland vegetation (Government and University of Alberta, 1969). Today, about 50 to 60 percent of the research basin has been cultivated and cleared. Nevertheless, the native parkland environment is still quite apparent, especially in the rougher terrain and along parts of the drainage system where farming is not yet feasible. The most important hydrological feature is the abundance of phreatophytes in depressional areas and drainage ways, which no doubt significantly influence the subsurface hydrology.

### CLIMATE

Fortunately, a meteorological station exists in the Pine Lake research basin and is located in Lsd 4 Sec 10 Tp 37 R 25 W4Mer. Although observations of temperature and precipitation have only been made since 1960, they are the best data currently available and probably represent conditions in at least the northern half of the research basin. Observations recorded at a station further south

**FIGURE 7.** Aerial view of Pine Lake, looking south from north end of lake.

in the Ghostpine Creek valley near Trochu (fig. 2) may be more characteristic of the climatic conditions at the south end of the research basin than the Pine Lake station. For that reason, data from both the Pine Lake and Trochu Equity stations are presented in tables 1, 2 and 3, which contain mean monthly values of precipitation, temperature, and potential evapotranspiration between 1941 and 1970.

Based on the available information, mean annual precipitation in the Pine Lake research basin probably varies from about 41 cm (17 in) in the southern part of the area, to over 48 cm (19 in) in the northern uplands. This estimate agrees quite closely with climatic maps of Alberta prepared by Longley (1968) for the record from 1931 to 1960. Of the total mean annual precipitation shown for the Pine Lake station in Table 1, rainfall was 36.7 cm (14.4 in) and mean snowfall was 126.5 cm (49.8 in) (Environment Canada, 1973).

The values of potential evapotranspiration are contained in table 3. They were calculated using the empirical method of Thornthwaite (1948). The mean annual potential evapotranspiration for the Pine Lake research basin is about 53 cm (21 in) in the south to less than 51 cm (20 in) in the northern region. The estimated average annual potential evapotranspiration is 50 to 56 cm (20 to 22 in) for the general region; actual evapotranspiration is 41 to 46 cm (16 to 18 in) (Government and University of Alberta, 1969). Figures 8 and 9 describe the relationship between precipitation and potential evapotranspiration for an average year in the Pine Lake area. These Thornthwaite diagrams show how precipitation exceeds potential evapotranspiration from mid-October to mid-April.

**TABLE 1.**
Mean monthly precipitation, Pine Lake research basin
(1941-1970)

| | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pine Lake cm | 2.13 | 1.80 | 1.63 | 3.43 | 5.87 | 8.51 | 8.00 | 6.99 | 4.83 | 2.59 | 1.93 | 1.56 | 49.28 |
| in | 0.84 | 0.71 | 0.64 | 1.35 | 2.31 | 3.35 | 3.15 | 2.75 | 1.90 | 1.02 | 0.76 | 0.62 | 19.40 |
| Trochu Equity cm | 1.93 | 1.80 | 1.91 | 2.90 | 3.73 | 7.47 | 7.11 | 5.59 | 3.53 | 2.31 | 1.65 | 1.73 | 41.66 |
| in | 0.76 | 0.71 | 0.75 | 1.14 | 1.47 | 2.94 | 2.80 | 2.20 | 1.39 | 0.91 | 0.65 | 0.68 | 16.40 |

**TABLE 2.**
Mean monthly temperatures, Pine Lake research basin
(1941-1970)

| | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pine Lake $^{o}C$ | -14.6 | -10.4 | -6.1 | 2.8 | 9.4 | 12.8 | 15.7 | 14.3 | 9.6 | 4.5 | -4.4 | -10.3 | 1.9 |
| $^{o}F$ | 5.7 | 13.2 | 21.0 | 37.1 | 48.9 | 55.1 | 60.3 | 57.7 | 49.2 | 40.1 | 24.0 | 13.4 | 35.5 |
| Trochu Equity $^{o}C$ | -14.3 | -10.0 | -5.4 | 3.5 | 10.3 | 14.7 | 17.3 | 16.4 | 11.1 | 5.1 | -4.7 | -10.5 | 2.8 |
| $^{o}F$ | 6.3 | 14.0 | 22.3 | 38.3 | 50.6 | 58.4 | 63.1 | 61.5 | 52.0 | 41.1 | 23.5 | 13.1 | 37.0 |

**TABLE 3.**
Mean monthly potential evapotranspiration, Pine Lake research basin
(1941-1970)

| | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pine Lake cm | - | - | - | 2.34 | 7.45 | 9.82 | 11.78 | 10.00 | 6.04 | 2.81 | - | - | 50.24 |
| in | - | - | - | 0.92 | 2.93 | 3.87 | 4.64 | 3.94 | 2.38 | 1.11 | - | - | 19.79 |
| Trochu Equity cm | - | - | - | 2.48 | 7.58 | 10.64 | 12.47 | 10.88 | 6.47 | 2.81 | - | - | 53.33 |
| in | - | - | - | 0.98 | 2.98 | 4.19 | 4.91 | 42.8 | 2.55 | 1.11 | - | - | 21.00 |

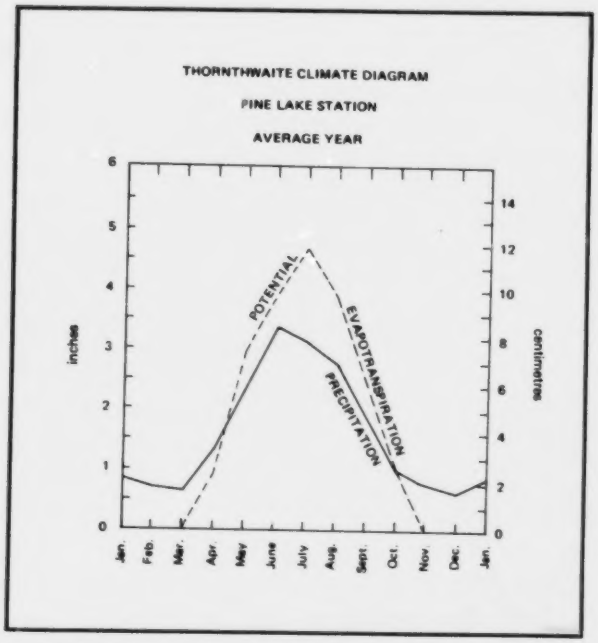


**FIGURE 8.** Graphical representation of climate at the Pine Lake meteorological station.

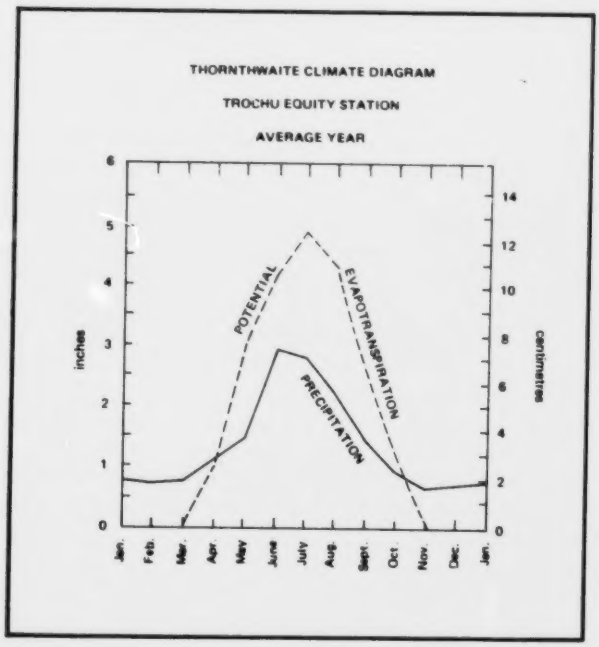


**FIGURE 9.** Graphical representation of climate at the Trochu Equity meteorological station.

## PHYSIOGRAPHIC FACTORS OF GROUNDWATER RECHARGE

The most important physiographic factor of groundwater recharge on the Canadian plains is climate. Figures 8 and 9 show that for an average year, potential evapotranspiration exceeds precipitation from April to October, thereby posing a major constraint to groundwater recharge. During the rest of the year, precipitation does exceed potential evapotranspiration, but the long cold winters effectively limit the period during which surface water can actually infiltrate into the ground and recharge the groundwater system. In the Pine Lake area, these potential recharge conditions occur during early October and late April when the ground is not frozen. Because precipitation is low in the fall (probably sufficient only to restore soil moisture), a major groundwater recharge is unlikely at that time. Only in late April to early May is the climate conducive to groundwater recharge. In this period, surface water is abundant from melting snow packs and high precipitation, evapotranspiration is low, and infiltration is not impeded by frozen ground. Even during periods of early thaw, frozen or partially frozen ground is probably not impermeable, so infiltration can take place (Williams and Burt, 1974).

A second major physiographic factor of groundwater recharge is topography. The water table, for instance, is a subdued replica of the topography. Regional topographic highs or uplands usually act as "recharge" areas because groundwater is naturally at a higher hydraulic head, so motion is directed towards areas of lower potential energy. Topographic lows are often discharge areas for groundwater flow. Another aspect of the effect of topography is that the unsaturated zone is likely to be considerably thicker in upland regions than in regional discharge areas. This has significant implications when interpreting groundwater chemistry, or the role of infiltration and unsaturated flow, as a component of the subsurface hydrologic cycle.

Drainage of the land has great importance in determining the actual quantities of precipitation that will be available for groundwater recharge. Some parts of the basin have integrated drainage and a considerable portion of the precipitation and snowmelt could be lost by runoff. In large

areas of hummocky upland, drainage is quite poor and surface water is detained in sloughs. Surface water in these areas has a much greater opportunity to infiltrate and recharge the saturated zone. The abundant growth of phreatophytic vegetation around these depressions combined with high summer evaporation will limit this recharge process mainly to early spring and to extended periods of summer rainfall. In the intermediate and lowland areas, local depressions probably act as groundwater discharge points, at least over most of the summer, but may contribute intermittently to groundwater recharge (Meyboom, 1966b).

The nature of the soils also influences groundwater recharge. In areas where drainage is poor, infiltration rates determine recharge rates. Infiltration and percolation are greatest in sandy-textured soils; in loams, surface water is more vulnerable to runoff and evapotranspiration.

## SURFACE WATER HYDROLOGY

Because surface water is an integral part of the hydrologic cycle, it has significant importance in basin-wide evaluation of the subsurface hydrology. Although data is limited, some general observations and interpretations of the surface water hydrology in the Pine Lake research basin can be made.

### STREAMFLOW

All streams in the research basin, including Ghostpine Creek, are intermittent, but are sometimes interrupted by perennial parts of the reach. Although they are shallow and narrow, these streams contain natural depressions that pond surface water, leading to an increase in evaporation losses. Furthermore, a large part of the annual precipitation ends up as streamflow, especially during periods of spring melt and summer storms.

The drainage area of the Ghostpine Creek basin, associated with the gauging station near Huxley*, is approximately 520 km² (200 sq mi). Although a major portion of this area is fairly well drained, the tracts of hummocky land in the basin do not drain well. Surface runoff in the hummocky areas usually amounts to overland flow into sloughs. Because the streamflow record is so short, and only a crude estimate of mean annual runoff was considered, the area of the basin actually contributing to total runoff was not determined. Based on the streamflow records, total runoff for 1967 amounted to $7.13 \times 10^6 m^3$ (5780 ac-ft), whereas the annual runoff for 1969 was $1.36 \times 10^7 m^3$ (11 000 ac-ft). Converting these figures to a depth over the 520 km² (200 sq mi) drainage area, annual runoff for 1967 is 1.37 cm (0.54 in) and for 1969 is 2.62 cm (1.03 in). The 1968 record was incomplete, so the runoff has not been calculated. With such a short period of record, it is difficult to judge how representative these figures are of the mean basin runoff.

The creek is almost completely frozen during the winter and therefore discharges can only be measured between spring thaw and late fall. As the 1967 hydrograph (fig. 10) illustrates, streamflow in Ghostpine Creek is intermittent. The major runoff in April depends completely on meltwater from the winter snowpacks. Although the runoff begins to recede after thaw, substantial rainfall in May, and especially June, briefly sustains streamflow. By early July, however, the low precipitation and high evapotranspiration rates deplete streamflow until it is almost negligible. By October, evapotranspiration losses have decreased so much that groundwater flows and minor amounts of rainfall only sustain daily streamflows of less than 0.014 $m^3/s$ (0.5 $ft^3/s$).

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*Quantitative streamflow records in the Ghostpine Creek drainage basin are scanty and for that part of the drainage basin in the Pine Lake research basin, nonexistent. Runoff observations have only been made for Ghostpine Creek. Measurements of creek stage were recorded for 1962 to 1966, but were not published. A discharge-type gauging station was established on Ghostpine Creek near Huxley (fig. 2) where discharge was recorded for the years 1967, 1968, and 1969. This gauging station was subsequently abandoned.

The complete streamflow records for the three years of discharge measurements are given in Environment Canada (1974). Table 4 is a summary of the streamflow data for the Ghostpine Creek station near Huxley. For purposes of illustration and discussion, the 1967 streamflow hydrograph and its corresponding hyetograph have been plotted in figure 10.

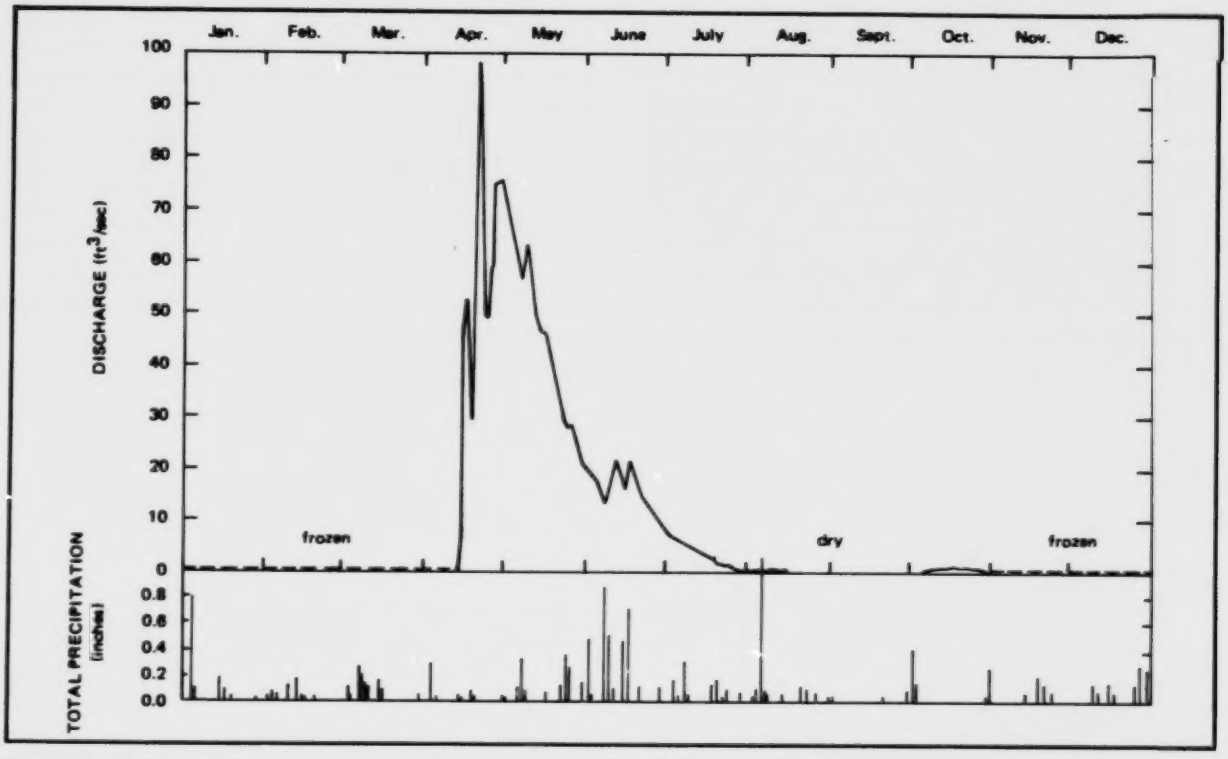



**FIGURE 10.** Ghostpine Creek streamflow hydrograph and Pine Lake station hyetograph, 1967.

The above description of streamflow indicates that the baseflow component of runoff is very small in the Ghostpine Creek drainage basin. In other words, groundwater discharge into the streams of the basin is often only sufficient to meet the demands of the frost-free months.

The actual amount of baseflow, or groundwater discharge, that contributes to streamflow in the April to June period is difficult to assess because of the large volume of surface runoff. Freeze (1969a) used minimum monthly discharges to estimate annual baseflow for several streams in a drainage basin in Saskatchewan. He pointed out that the baseflow in these intermittent streams may or may not represent total groundwater discharge, but that such figures could be correlated with mean annual groundwater recharge.

In any event, this procedure amounts to 2.2 x $10^6 m^3$ (1780 ac-ft) or 0.43 cm (0.17 in) over the drainage area associated with the Ghostpine Creek gauging station for the 1967 record. The figures for the 1969 record are 1.4 x $10^6 m^3$ (1120 ac-ft) or 0.27 cm (0.11 in) respectively. Whether or not these values accurately represent groundwater discharge is debatable.

## LAKES AND SLOUGHS

Comparison of aerial photographs taken in 1975 with topographic maps of 1970 and 1959 show that all lakes in the Pine Lake research basin are permanent bodies of surface water, although a few have varied slightly in area over the past 25 years. Pine Lake is the largest reservoir of surface water.

Figure 11 shows the results of a 1967 hydrographic survey of Pine Lake by the Surveys Branch, Alberta Department of the Environment.

Lake levels have been recorded since 1965, but daily observations, based on a 1.5 m fiberglass staff gauge at the north end of Pine Lake, have only been available since 1973. The lake level

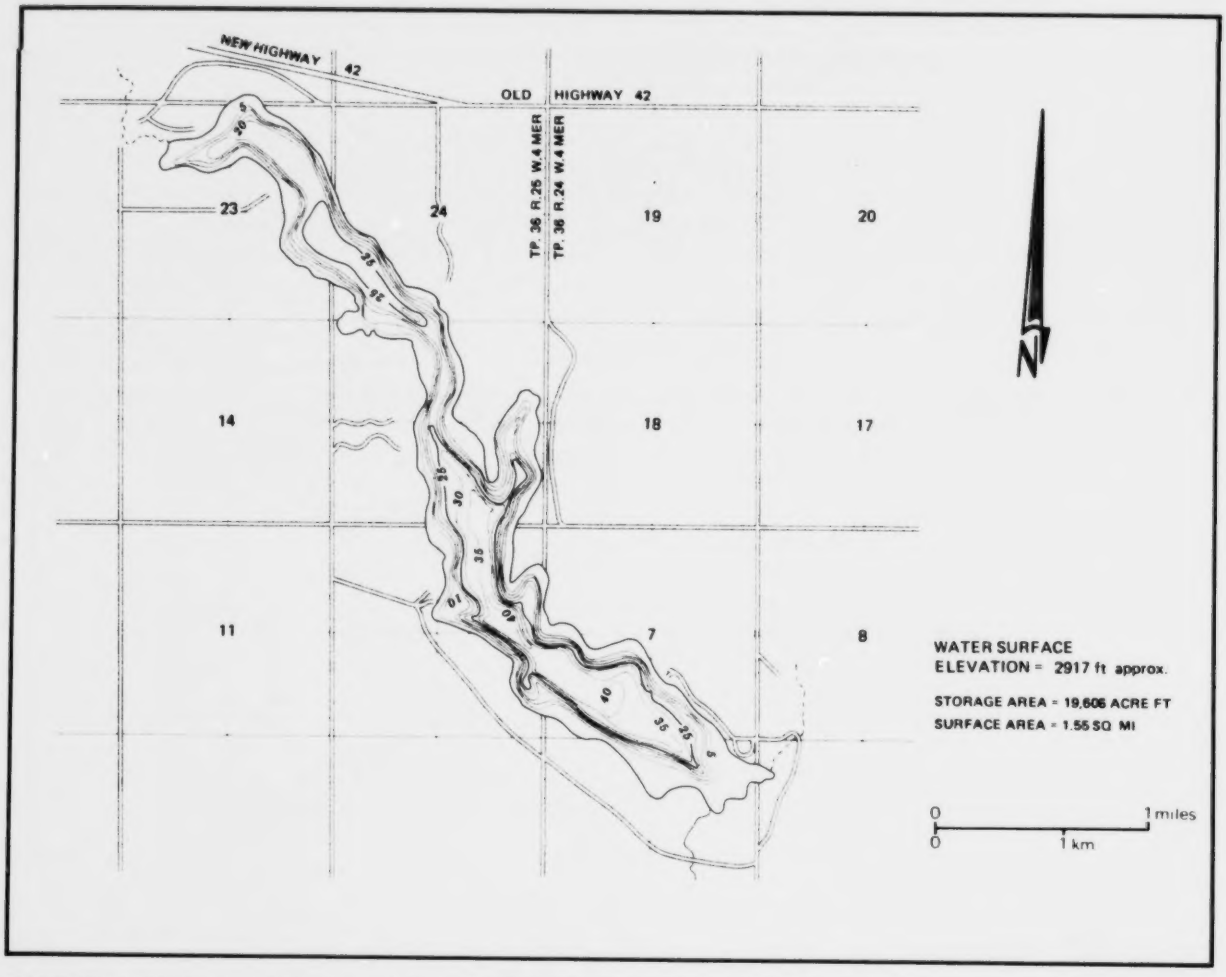



**FIGURE 11.** Hydrographic map of Pine Lake (after Surveys Branch, Alberta Department of the Environment, 1967). Contours represent lake depth, in feet.

hydrographs for the years 1973, 1975, 1976, and 1977 are shown in figure 12. The 1974 record is incomplete, so has not been plotted. Pine Lake is completely frozen over from about November to the end of April.

A recession curve analysis of the lake level hydrographs is shown in figure 12 and the results tabulated in table 5. The net evaporation from June 1 to October 1 was calculated by adding the lake level drop, based on the recession curves, to the observed precipitation for that period. According to maps produced by Bruce and Weisman (1967), this four-month period would account for about 80 percent of the annual evaporation. Therefore, the annual evaporation for each year of record was calculated by dividing the June 1 to October 1 figures by 0.80. The mean value of annual net evaporation was determined to be about 48 cm (19 in). This is not the actual evaporation rate for Pine Lake. Inadequate records of runoff and estimates of seepage out of the lake bottom, groundwater discharge, and near shore transpiration prevent calculation of a meaningful evaporation rate. Bruce and Weisman (1967) constructed lake evaporation maps of Canada, using evaporation pan data and solar radiation measurements. Based on their map, mean annual lake evapora-

## TABLE 4.

Summary of streamflow data, Ghostpine Creek near Huxley

Ghostpine Creek near Huxley - Station No. 05CE012
Monthly and Annual Mean Discharges in cubic feet per second for the period of record

| YEAR | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEP | OCT | NOV |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1967 | - | - | 0.0 | 31.6 | 44.1 | 15.8 | 3.5 | 0.17 | 0.0 | 0.34 | 0.31 |
| 1968 | - | - | 5.9 | 2.4 | 1.2 | - | - | 4.0 | 2.4 | 1.0 | - |
| 1969 | - | - | 0.0 | 137.0 | 20.5 | 4.2 | 5.6 | 2.7 | 5.2 | 7.3 | - |
| MEAN | - | - | 2.0 | 57.0 | 21.9 | 10.0 | 4.6 | 2.3 | 2.5 | 2.9 | 0.31 |

LOCATION - Lat 51 53 40 N
Long 113 14 20 W

NATURAL

Ghostpine Creek near Huxley - Station No. 05CE012
Drainage Area = 200 Sq Miles
Annual Extremes of Discharge in CFS and Annual Total Discharge in AC-FT for the period of record

| YEAR | MAXIMUM INSTANTANEOUS DISCHARGE | MAXIMUM DAILY DISCHARGE | MINIMUM DAILY DISCHARGE | TOTAL DISCHARGE |
|---|---|---|---|---|
| 1967 | - | - | - | - |
| 1968 | - | 31.6 CFS ON AUG 5* | 0 CFS ON JUL 18* | - |
| 1969 | 1110 CFS AT 1820 MST APR 6 | - | - | - |

* - Extreme recorded for the period of record.

## TABLE 5.

Results of recession curve analysis of lake level hydrographs - Pine Lake

| Year | Lake Level Drop June 1 - Oct 1 (inches) | Precipitation June 1 - Oct 1 (inches) | Net Evaporation June 1 - Oct 1 (inches) | Net Annual Evaporation |
|---|---|---|---|---|
| 1973 | 3.12 | 14.55 | 17.67 | 22.09 |
| 1974 | - | - | - | - |
| 1975 | 7.32 | 7.24 | 14.56 | 18.20 |
| 1976 | 2.40 | 10.95 | 13.35 | 16.69 |
| 1977 | 2.64 | 12.44 | 15.08 | 18.85 |

Mean Annual Net Evaporation = 18.96 inches = 48.15 cm

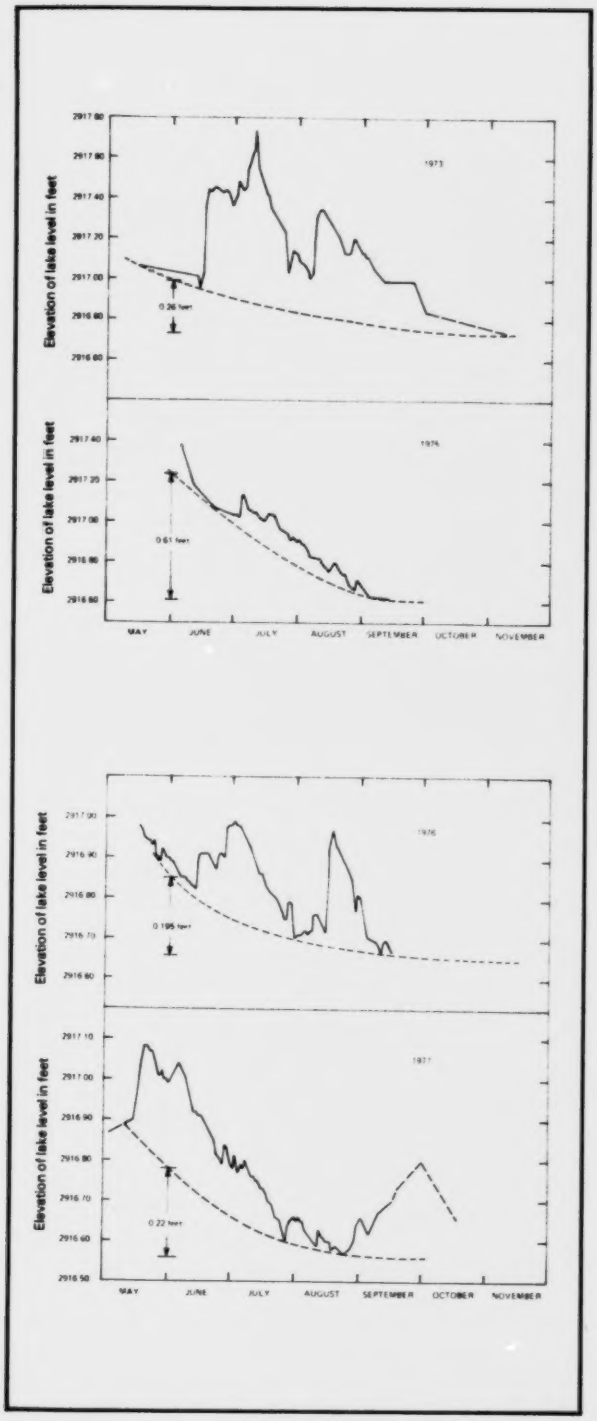



**FIGURE 12.** Lake level hydrographs, Pine Lake.

tion for the Pine Lake area should be about 74 cm (29 in). Their evaporation estimates, however, apply only to water bodies with small heat storage, such as ponds and shallow lakes, an assumption that may not hold for Pine Lake.

The importance of sloughs to the surface-water hydrology of the Pine Lake area has already been recognized in the earlier discussions of drainage.

The topographic map of the Pine Lake basin does not illustrate the abundance of sloughs in this hummocky area. The aerial photograph in figure 13 better represents their distribution and character.

The presence of sloughs in an area effectively limits surface runoff by acting as small, closed-drainage basins. In effect, they interrupt development of an integrated drainage system, thereby enhancing evaporation, transpiration, or infiltration. Unfortunately, water budget data is not available for the hydrology of sloughs in the Pine Lake area. Freeze (1969b) found that, for a water budget of a parkland region in Saskatchewan, the evaporation rate for sloughs could be assumed to be 80 percent of the annual rate of that for lakes. If this holds true for the Pine Lake area, annual slough evaporation would be estimated at 59 cm (23 in).

Several studies have shown that sloughs significantly affect the local groundwater regime. Sloughs can behave strictly as focal points of groundwater recharge, as groundwater discharge features, or possibly as an intermediate combination of both as a throughflow. In fact, Meyboom (1966b) found an annual sequence of transient flow conditions in Saskatchewan. In short, the surface-water hydrology, groundwater hydrology, and water budget of an individual slough can be complex.

## GEOLOGY

### GEOLOGICAL SETTING AND REGIONAL STRATIGRAPHY

In south-central Alberta, glacial deposits of the Pleistocene continental glaciation and Recent alluvium form a veneer over bedrock strata of Upper Cretaceous and Tertiary age. Excellent

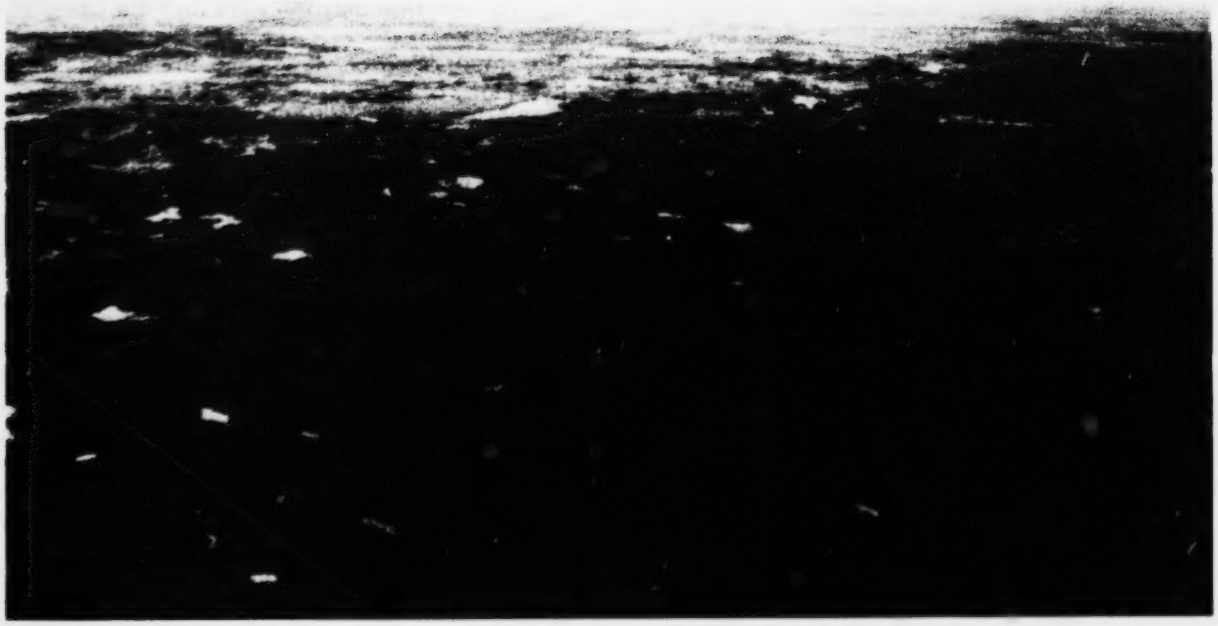


**FIGURE 13.** Aerial view of hummocky terrain with sloughs, Pine Lake research basin.

exposures of the bedrock formations are found along sections of the Red Deer River. Underlying these rocks are a thick succession of Lower Cretaceous and Paleozoic strata, many containing commercial quantities of oil and gas. Depth to Precambrian basement is over 3 000 m (10 000 ft). Figure 14 summarizes the regional nature of the bedrock and the deeper stratigraphy in central Alberta.

The Pine Lake basin is characterized by a relatively thin mantle of surficial deposits, usually less than 15 m (50 ft) thick, but locally exceeding 45 m (150 ft). The entire area is underlain by semiconsolidated to consolidated sandstones, siltstones, and shales of the thick Paskapoo Formation, which constitutes the bedrock (Rutherford, 1939; Allan and Sanderson, 1945; Green, 1970). Table 6 is a stratigraphic chart of the formations in the Pine Lake basin, down to and including the Lea Park Formation. Information about the units below the Paskapoo Formation is based on interpretation of geophysical logs from deep oil and gas wildcat wells (fig. 5) and on the compilation by Green (1970). The Paskapoo Formation and glacial drift, which combined exceed 300 m (1000 ft) in thickness, are the focal points for the remainder of this report. In relation to groundwater hydrology, the Paskapoo Formation and drift undoubtedly contain all hydrostratigraphic units that would be of theoretical and practical importance. Furthermore, these shallow rock units are basically the only deposits for which detailed geologic, geophysical, and hydrogeologic data are available.

## PASKAPOO FORMATION

### Definition and Nomenclature

Allan and Sanderson (1945) made the first extensive study of the Paskapoo rocks in south-central Alberta. They noted that, in general, the Edmonton Rocks are clayey and impervious whereas the Paskapoo rocks absorb surface water readily and, at many locations along the

**TABLE 6.**
Stratigraphic chart of formations, Pine Lake area

| Era | Period | Epoch | Group or Formation | | Lithology | Thickness |
|---|---|---|---|---|---|---|
| Cenozoic | Quaternary | Pleistocene | "Glacial Drift" | | till; lacustrine sand, silt, and clay; outwash sand and gravel | 0 - 50 m (0 - 170 ft) |
| | Tertiary | Paleocene | Paskapoo Formation | | gray, thick-bedded, calcareous cherty sandstone; gray and green siltstone and shale; minor coal and tuff beds<br>— — — — — —<br>Scollard Member: feldspathic sandstone and bentonitic shales; thick coal beds (nonmarine) | 76 - 300 m (250 - 1000 ft)<br>— —<br>30 - 75 m (100 - 250 ft) |
| Mesozoic | Cretaceous | Upper Cretaceous | Edmonton Group | Battle Formation | purplish-black bentonitic mudstone; siliceous tuff beds | 4 - 9 m (15 - 30 ft) |
| | | | | Whitemud Formation | pale gray-white bentonitic sandstone | 4 - 6 m (15 - 20 ft) |
| | | | | Horseshoe Canyon Formation | gray, feldspathic, clayey sandstones and mudstone, carbonaceous shale; coal and bentonitic beds; minor thin limestones (mainly nonmarine) | 400 - 425 m (1300 - 1400 ft) |
| | | | Bearpaw Formation | | dark gray shale and silty shales; minor sandstones (marine) | 30 - 75 m (100 - 250 ft) |
| | | | Belly River Formation | | gray, thick-bedded, feldspathic sandstones; gray clayey siltstone; gray and green mudstone (nonmarine) | 200 - 290 m (650 - 950 ft) |
| | | | Lea Park Formation | | dark gray shale; pale gray silty shale (marine) | 140 - 180 m (450 - 600 ft) |

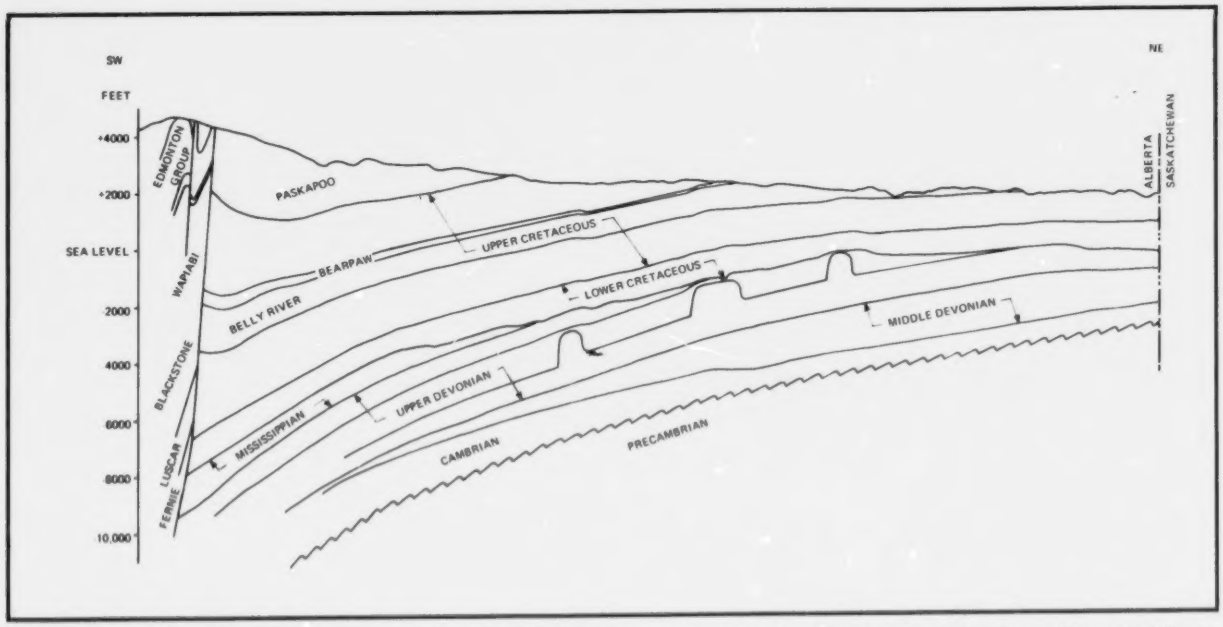



**FIGURE 14.** Diagrammatic cross section through central Alberta (after Geological Highway Map of Alberta, Canadian Society of Petroleum Geologists 1975). Vertical Exaggeration is 20:1.

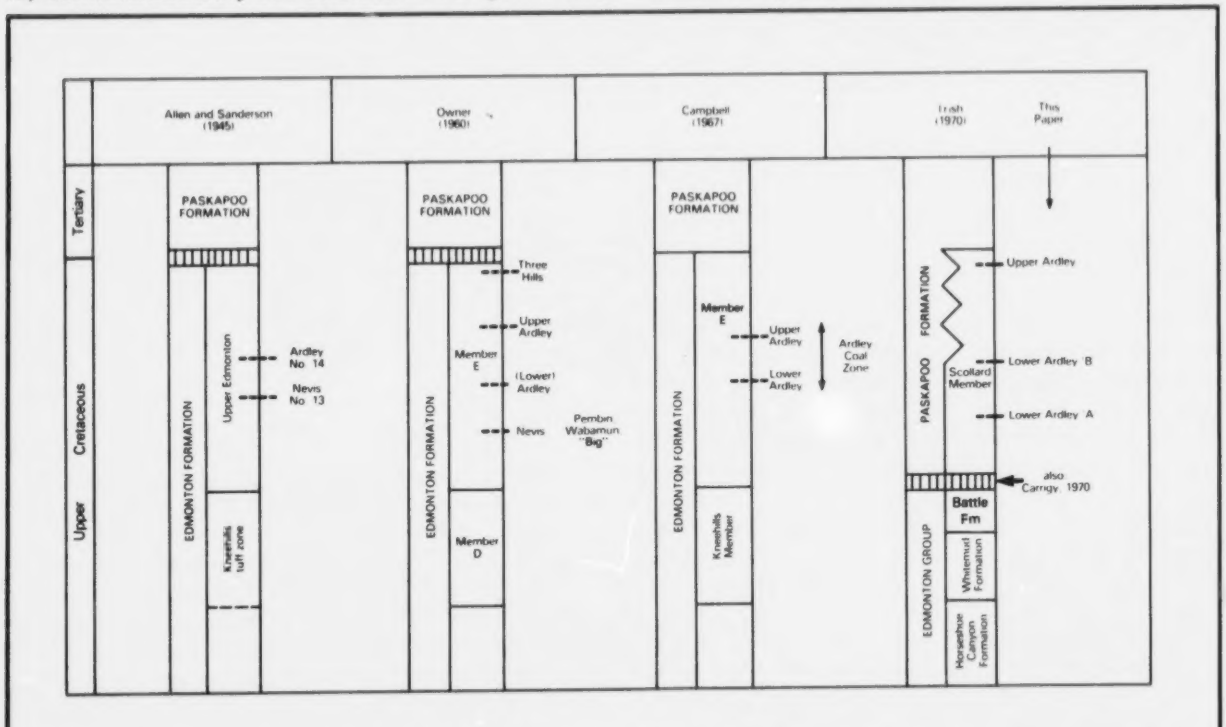



**FIGURE 15.** Stratigraphic table summarizing nomenclature of the Edmonton Group and Paskapoo formation (after Holter, Yurko, and Chu, 1975).

valley of the Red Deer River, the contact between these two formations is marked by numerous springs. A further contribution by Allan and Sanderson (1945) was the identification of a widespread volcanic ash unit in the upper part of the Edmonton strata, later named the Kneehills tuff.

Since the study of Allan and Sanderson (1945), many geologists have improved upon the stratigraphy of the Edmonton-Paskapoo strata. Ower (1960) devised a detailed division of strata and concluded that the upper boundary of the Edmonton Formation be placed at the first thick sandstone above an extensive coal bed known as the Ardley. Campbell (1967) used Ower's subdivision in his detailed examination of the Ardley coal zone but stressed that the transitional nature of the strata made the Edmonton-Paskapoo boundary arbitrary. Carrigy (1970) proposed that the lower boundary of the Paskapoo Formation should be accepted as the top of the Kneehills tuff unit (Battle Formation) in central Alberta. Irish (1970) concurred with this boundary revision and completely modified the Upper Cretaceous-Tertiary nomenclature of central Alberta. Holter, Yurko, and Chu (1975) contributed further stratigraphic knowledge of the Paskapoo Formation in their study of the Ardley coal zone. They were able to map three main coal units; Lower Ardley 'A', Lower Ardley 'B', and the Upper Ardley. These relationships are summarized in figure 15.

The terminology of Irish (1970), which is currently the most widely accepted, is adhered to in this report. As an example of the nomenclature of Irish (1970), figure 16 shows a representative subsurface section of the Paskapoo Formation in the Pine Lake research basin. The Upper Ardley coal zone appears to be absent or poorly developed over much of the Pine Lake area and, therefore, the Lower Ardley 'B' has been chosen as the marker bed for the top of the Scollard Member.

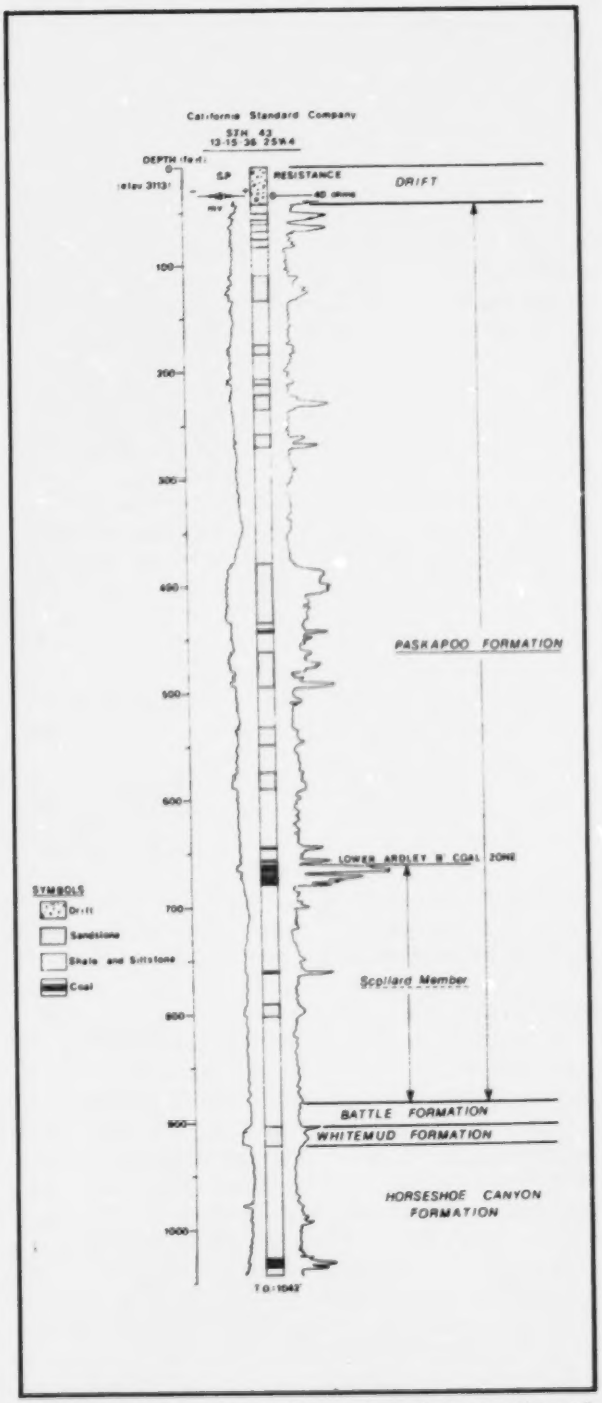



**FIGURE 16.** Representative subsurface section of the Paskapoo formation in the Pine Lake research basin.

## Lithology

Irish (1970) described the general lithology of that part of the Paskapoo Formation above the Scollard Member as consisting of massive, in part cross-bedded, coarse-grained, buff-weathering, gray calcareous sandstones; well-indurated to soft, fine-grained sandstones and siltstones; and green to gray, friable, silty shales. Although the

sandstones are dominated by quartz with minor amounts of feldspar, fragments of shale, carbonate, chert, quartzite, and clay pellets comprise an important percentage which typically gives these sands a "salt and pepper" textural appearance (Allan and Sanderson, 1945). Also present in this section of the Paskapoo Formation are thin beds of argillaceous and siliceous, fossiliferous limestone, lenses of pebble conglomerate, thin beds of woody coal, carbonaceous shale, bentonitic clays, and local bands of laminated lacustrine clays.

The Scollard Member is characterized by a lithological succession similar to that described above, except that beds exhibit a greater degree of interlensing and thick, extensive coal seams are prominent. As noted earlier, a maximum of three major coal units (Lower Ardley 'A', Lower Ardley 'B', and Upper Ardley) are discernible in the Scollard Member.

Bedrock exposures (Paskapoo Formation) in the Pine Lake area are relatively scarce (see fig. 4) and appear to have been created by road construction. Thickly bedded to massive sandstones dominate most of these exposures, although bentonitic grayish-brown clays and hard bluish-green, carbonaceous shale were at a road cut near the north end of Pine Lake.

In the subsurface, lithologic logs from water well drillers' reports usually contain descriptions of the Paskapoo Formation as consisting of interbedded gray to green shale, gray sandy shale (siltstones?), and soft gray sandstone. Drillers frequently describe these rocks as bentonitic and when oxidized are commonly listed as yellow to brown shales or sandstones. Thin woody coal seams, highly fractured shales, and very hard sandstone beds are also encountered during water well drilling in the Pine Lake area. The numerous wells in most parts of the basins provide a good account of the lithology down to about 100 m (300 ft) on the ridges and to about 30 m (100 ft) near the valley bottom. Lithological descriptions of the Paskapoo Formation at greater depths is limited to four coal testholes and four groundwater testholes. All of these drill holes penetrate the section of Paskapoo strata above the Lower Ardley 'B' but none were drilled through the entire Scollard Member.

**Lithostratigraphy**

The nature and distribution of lithostratigraphic units is of primary concern in hydrogeologic investigations because of the influence on the distribution of aquifers. Stratigraphic relationships also impose strong control on the groundwater flow pattern in a sedimentary basin.

As explained earlier, the regional stratigraphy of the Upper Cretaceous-Tertiary strata is based almost entirely on lithologic criteria and areally persistent marker beds such as the Kneehills tuff (Battle Formation) and Ardley coal zone (Scollard Member). For hydrogeologic purposes, a greater degree of refinement is needed. Although abundant lithologic logs are available for the shallow bedrock, subsurface geologic information on deeper sections of the Paskapoo Formation is scarce. Fortunately, an excellent distribution of electric logs (fig. 5) from relatively deep (maximum 380 m) structure testholes exist in the Pine Lake area. These logs consist of a spontaneous-potential and a single-electrode resistance curve, both of which appear to be quite responsive to various lithologies (for example sandstone, shale, coal, and drift). Figure 16 is an example of a structure testhole electric log and the typical log responses. Reliable interpretation of the structure testhole electric logs was made by comparing their responses to the logs of the coal tests.

Several geological sections, based largely on the interpretation of electric logs, were constructed in order to determine the subsurface lithostratigraphy of the Pine Lake research basin. These sections are shown in figures 17 to 23 and their locations are given in figure 5. Because most of the structure testholes and coal testholes rarely penetrated the entire Scollard Member of the Paskapoo Formation, the lithostratigraphy below the Lower Ardley 'B' coal zone has not been illustrated. Several electric logs of the Scollard Member indicate that it is essentially a shale-siltstone unit in the Pine Lake area, although it is not completely devoid of sandstone (fig. 16). Information presented on the cross sections is also supplemented by geologic logs of water wells and a few radioactivity logs of cased oil and gas wells.

The geological sections show three major lithostratigraphic units in the subsurface; glacial drift,

sandstones, and mudstones (shales and siltstones). The stratigraphic detail of the glacial drift is not shown on these diagrams because all drift deposits have been lumped as a single lithostratigraphic unit. Only the major units of sandstone have been represented; zones of predominantly sandstone are shown as solid units. Therefore, thin beds of sandstone may be found in those parts of the sections shown as shale and siltstone and vice versa.

The most prominent stratigraphic feature in the geological sections (figs. 17 to 23) is the areally persistent nature of the Lower Ardley 'B' coal zone. This coal is easily detected on electric logs (fig. 16) and characteristically occurs as two major coal beds, which are less than 2 m (6 ft) thick, separated by a shale and bounded at top and bottom by minor coals and shaly coals. A few minor coal seams exist above the Lower Ardley 'B', but their extent in the Pine Lake area is difficult to assess. These thin coals were not correlated because the thick Ardley was more than sufficient for the purposes of this study.

The generalized cross sections illustrate several other important stratigraphic features. Although correlation of sandstone units in the Paskapoo Formation is difficult, the task is not impossible. The Paskapoo Formation is often described as consisting of strata that are irregularly distributed and of a lenticular nature. The geological sections through the research basin appear in part to support this general observation. Nevertheless, correlation of sandstone units over several miles is possible, although the complexity of this task may vary from being rather simple (section A-A*) to quite complicated (section B-B*). Individual sandstone units, which can be mapped over substantial distances, are usually greater than 5 m (15 ft) in thickness and in some areas of the basin many sandstone beds appear to coalesce, forming units of sandstone that are over 100 m (300 ft) thick.

Figure 24 summarizes the areal variation in lithologies over the basin. It is a sandstone percentage map of that part of the Paskapoo Formation above the Lower Ardley 'B' coal zone. A more sophisticated facies map could have been constructed, but hydrogeologically this simple map is sufficient to outline the areal variation in lithology. The Paskapoo Formation in the Pine Lake research basin is a shale-siltstone sequence, particularly in a large area west of Pine Lake where over 80 percent of the strata are mudstones. A prominent northwest-trending sandy lobe extends into the western edge of the basin but quickly dissipates. Sandstone comprises up to 70 percent of the section in the area immediately southeast of the basin, of which a major sandy lobe extends northward forming part of the basin's eastern ridge.

**Structure and Thickness**

In the subsurface, the Lower Ardley 'B' coal zone is an excellent marker bed for examining the structure of the Paskapoo Formation. Figure 25 shows the elevation on top of the Lower Ardley 'B' coal zone in the Pine Lake research basin. The structure contours largely trend north-south, although perturbations in the contour pattern are readily apparent. One structural trend appears to coincide with the western divide of the basin, while another major undulating trend in the contours sweeps across the basin in the east-west fashion near the north end of Pine Lake. A few isolated and closed structural highs and depressions are also found in the area. Although direct evidence of faulting and folding of Paskapoo strata in the Pine Lake area is not available, the undulating trends on the structure contour map suggest that gentle flexures in the strata probably occur locally. In fact, the geological sections C-D*, D-D*, and E-E* (figs. 19, 20, and 21) appear to illustrate a noticeable (but almost imperceptible) depression of the sandstone units towards the drainage way of the research basin and a gentle rise towards the ridges which form the drainage divides. The Ghostpine Creek drainage basin may therefore represent a broad gentle flexure of the bedrock strata. Allan and Sanderson (1945) recognized the regional nature of this feature and hypothesized that much of the parallelism of stream courses west of the Red Deer River (fig. 2) could be attributed to the direction of folding.

The thickness of the Paskapoo Formation in the Pine Lake basin ranges from about 110 m (350 ft) in the south to over 360 m (1200 ft) in the northern part of the basin. For that part of the stratigraphic sequence above the Lower Ardley 'B' coal, the thickness ranges from around 75 m to 300 m (250 to 1000 ft). The areal variation in thickness of this

unit across the research basin is well illustrated by the geological sections.

### Bedrock Topography

The upper boundary of the Paskapoo Formation in the Pine Lake area is an erosional surface, uncomformably overlain by glacial deposits of Pleistocene age. Figure 26 is a contour map showing the elevation of the bedrock strata, which in turn represents the preglacial surface topography of the research basin. The main source of data used in constructing this map was the elevation of the glacial drift-bedrock contact in boreholes, supplemented by elevations of bedrock exposures, and interpretation of electric logs.

The most prominent feature of the bedrock topography in the research basin is that it closely reflects the general nature of the present topographic highs. Bedrock valleys are found along existing drainage ways, except where the present terraine is quite hummocky. The contour map (fig. 26) shows that what is now Ghostpine Creek, Pine Lake, and their tributaries was a northwest-trending, relatively deeply incised, southward flowing drainage system. This preglacial bedrock valley is named the Archithinue Valley. The present Ghostpine Creek system has a maximum relief in the research basin from valley bottom to adjacent plateau of about 45 m (150 ft). The Archithinue Valley was a much more deeply incised feature with relief as much as 75 m (250 ft). Ghostpine Creek is an underfit stream meandering in the location of a broad and deep valley bottom which was eroded before the Pleistocene glaciers advanced and is now partly buried by unconsolidated deposits.

## GLACIAL DRIFT

### Definition and Nomenclature

"Glacial drift" is used here to refer to the unconsolidated Pleistocene deposits of boulders, till, gravel, sand, silt, or clay that were formed as a result of continental glaciations. Although minor amounts of Recent alluvium exist, no deposits of the preglacial Saskatchewan Gravels and Sands (Stalker, 1960), which usually are associated with the preglacial valley of the Red Deer River, are present in the Pine Lake research basin.

### Distribution and Lithology of Drift Deposits

The surficial geology of the research basin (fig. 27) is characterized by extensive ground moraine and hummocky moraine. Both of these deposits consist of till or boulder clay which is the most abundant surficial material in the study area. The till is comprised largely of sediments derived from the local bedrock (Paskapoo Formation and Edmonton Group) but also includes rock fragments of igneous and metamorphic origin as well as hard sandstones and carbonates from distant areas. Much of the till in the Pine Lake area is sandy because of the prominence of the Paskapoo Formation. Hummocky moraine, typically thicker than the ground moraine deposits, is found in areas of high elevation and characterized by knob-and-kettle topography. The hummocky moraine also includes numerous pockets and hills of sand and gravel and is associated with short esker ridges, kames, wind gaps, and dead-ice plateaus (fig. 27). Ground moraine was deposited mainly from the base of the glacier as a consistent and even blanket of till. Stalker (1960) describes these till deposits as compact, dense, and very sticky when wet due to the abundance of bentonite derived from the local bedrock. In general, tills have a very low hydraulic conductivity, although it may increase slightly where material is sandy or jointing is common.

### Thickness

Figure 28 shows the total undifferentiated thickness of the glacial drift in the Pine Lake research basin. The most conspicuous feature delineated on this isopach map is the thickening of the drift deposits towards the thalweg of the Ghostpine drainage way. Borehole data indicate that the thickness of the drift along this preglacial valley can exceed 45 m (140 ft). Drift deposits are also more than 30 m (100 ft) thick in other parts of the research basin, especially in areas where strongly developed hummocky moraine is dominant (compare figures 27 and 28). The most outstanding example of this feature is found in an area just north of the research basin divide in township 37, range 25. Over 50 m (160 ft) of drift was encountered in two testholes in this area and several others penetrated drift more than 40 m

(130 ft) thick. Contouring drift thickness in these regions is very difficult and probably misleading; for the completeness of the map, however, it has been included in figure 28. In reality, smooth isopach patterns probably do not exist. The character of hummocky moraine is such that drift thickness should be expected to change abruptly and therefore the true situation would be much more erratic than that depicted in figure 28.

### Stratigraphy

Figure 29 shows the subsurface geology of the drift deposits as interpreted from drillers' logs of water wells. The detail of the analysis is limited because of the complexity of the geology and quality of data. Two major tills are discernible in the subsurface: a blue till and a gray till. The blue till is widespread in the northern part of the study area and is typically blue-gray, dark blue, or sometimes black, very sticky, and clay-rich relative to the gray till. The dark color imparted to this till is possibly due to a high content of carbonaceous material and length of burial under saturated conditions. This material, however, retains its dark color even when near the surface and in the unsaturated zone. Gray till is the most abundant drift material in the research basin. Drillers often describe these deposits as gray sandy clay till or, if oxidized, as various shades of yellow and brown. Compared to the blue till, the texture of the gray till appears less massive or dense and possibly more permeable. Figure 29 indicates that the blue till is usually a basal unit overlain by gray till (see, for example, well number 160) or by sands and silts (see well number 291). At some locations, however, blue till is also underlain by gray till or sand (see well numbers 338 or 354).

The abundance of outwash and glaciolacustrine sands and silts along the preglacial drainage way is as apparent in figure 29 as on the surficial geology map. Borings made along this thalweg penetrate thick deposits of interbedded gravel, sand, and silt, whereas further away from the drainage way these sediments become integrated with the tills, in places forming an obvious intertill deposit. Significant amounts of stratified drift area also occur near the ridge forming the divide in the southwest part of the research basin. The deposits in this area may in part be associated with ice-contact drift rather than outwash.

## HYDROGEOLOGY

Hydrogeology can be defined as the science that deals with the occurrence, distribution, and movement of groundwater, its relation to the subsurface and surface environment, and the nature of groundwater chemistry. Fundamental to this definition are two concepts, the hydrogeologic environment and the groundwater regime. The hydrogeologic environment refers to those aspects of topography, geology, and climate influencing groundwater conditions. Tóth (1970) described the groundwater regime as a number of parameters representing the physical and chemical conditions of groundwater. Thorough study of the groundwater regime would involve investigating the amounts of water present in the saturated zone, pattern of groundwater flow, volume discharge or flow velocity, chemical composition, water temperature, and the variance of these parameters with time. Theoretically, the relationship between the hydrogeologic environment and the groundwater regime is genetic and quantitative and can be mathematically modelled, provided sufficient field information is obtained and the physics of the system understood.

The basic goals of a hydrogeologic investigation of a basin are to determine:

1. the hydrogeological environment;
2. the groundwater flow systems;
3. its interaction with surface hydrology through recharge and discharge;
4. the chemistry of groundwater and its relation to other regime parameters;
5. the quantitative hydrologic properties of subsurface materials with special emphasis on aquifers and the groundwater budget of the basin; and,
6. the groundwater resources in regard to existing demands, potential development, and environmental considerations.

This study so far has dealt with the hydrogeologic environment. The balance of the report will deal with these other aspects of the groundwater study of a basin.

## THE ANALYSIS OF GROUNDWATER FLOW

Subsurface flow patterns can be deduced from either theoretical considerations or the analyses

of field techniques. The theoretical approach relies on the fact that groundwater flow obeys the laws of physics and, therefore, can be rigorously modelled mathematically, provided boundary conditions and the hydrogeologic environment are known. Field techniques also make use of the hydrogeologic environment in interpreting flow patterns. These techniques may consist of several types of analyses, commonly grouped as follows:

1. piezometric or potentiometric analyses;
2. interpretation of hydrogeochemistry;
3. evaluation of groundwater field phenomena (surficial evidence);
4. determination of groundwater temperature distribution; and,
5. use of environmental isotopes.

The first three methods are used most frequently in regional groundwater flow studies, and are the only ones considered in this analysis.

The theoretical approach to the steady-state analysis of regional groundwater flow was first established in the classic treatise on the theory of groundwater motion by Hubbert (1940). He showed that groundwater flow is governed by a potential field represented by hydraulic head. Tóth (1962, 1963) expanded on Hubbert's work by applying the concept that exact groundwater flow patterns can be obtained mathematically as solutions to formal boundary-value problems. He documented this concept by using analytical methods to solve Laplace's equation for the potential distribution in a two-dimensional model of a small, homogeneous drainage basin. He also developed the concept of groundwater flow systems.

The analytical technique provided by Tóth (1962, 1963) aided in the investigation of the parameters involved in regional groundwater flow. The solutions were limited, however, to specific field conditions with simple basin geometry and geology. This situation was significantly improved with the advent of numerical methods in groundwater hydrology. Freeze and Witherspoon (1966, 1967, 1968) used two and three dimensional finite difference models to simulate groundwater flow in field conditions. These models included anisotropic, heterogeneous groundwater basins with complex water-table configurations. Their study demonstrated how the shape of the water table and underlying hydraulic conductivity contrasts influence the groundwater flow pattern. Figure 30 shows the flexibility of the numerical method. Freeze (1969a) also showed how the theoretical approach can be integrated with field techniques to form a powerful tool for delineating groundwater flow systems.

Research in numerical modelling in the past decade has rapidly advanced the state of theoretical analysis of groundwater flow. Numerous finite difference, finite element, and integrated finite difference models have been designed to treat a broad spectrum of hydrogeologic conditions: steady-state or transient flow, in two or three dimensions and with complex boundary conditions; saturated-unsaturated flow; problems of flow in the

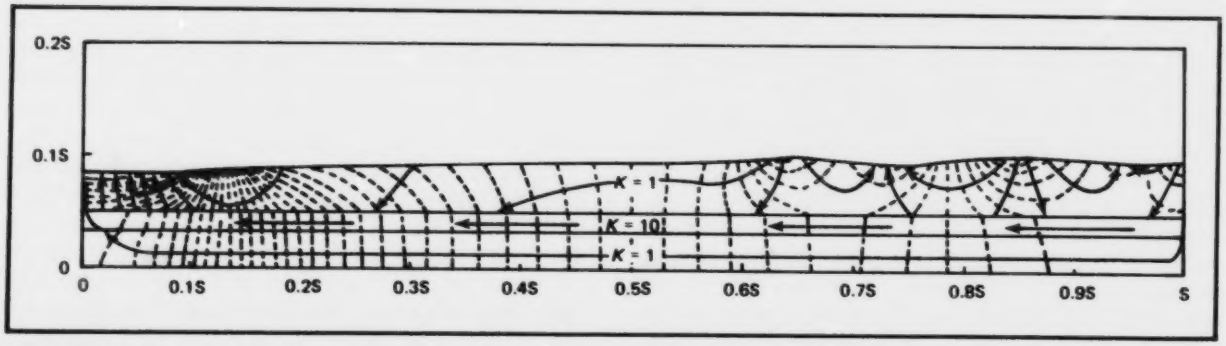



**FIGURE 30.** Hydrogeologic section showing theoretical flow patterns as determined by finite difference model (after Freeze, 1969c).

presence of free surface and seepage face; mass or solute transport; and flow in fractured rock media.

One recent application of numerical methods by Winter (1976, 1978) is important to the Pine Lake research basin. He employed a finite difference model to simulate in two and three dimensions the steady-state pattern of groundwater flow systems near lakes in a glacial terraine. Boundary conditions in the models were the same as those prescribed by Tóth (1962, 1963) and Freeze (1969a) in their groundwater basin studies. Figure 31 shows one of Winter's hydrologic sections of a multiple-lake system in a homogeneous but anisotropic basin. Based on the potential distributions derived for various hydrologic sections, Winter (1976, 1978) documented the nature of the interaction between lakes and groundwater. He concluded that the continuity of the boundary separating local from regional flow systems determines whether the lake is a recharge, discharge, or throughflow system. Factors affecting this flow system include the height of the water table (relative to the lake level) on the downgradient side of the lake, lake depth, geometry and hydraulic conductivity of aquifers, and the degree of anisotropy.

A detailed theoretical investigation of flow systems in the Pine Lake basin has not yet been attempted. The preliminary results of a simple numerical simulation, however, will be presented later.

## WATER-TABLE CONFIGURATION

The water table in the Pine Lake basin is a subdued replica of the topography. Field observations, and reported water levels, indicate depths of less than 5 m (20 ft) below land surface. The water table does not always conform to local topographic relief. The depth and shape of the water table in part reflect subsurface permeabilities in the Pine Lake area.

According to Freeze (1969c), the assumption of a steady-state water table is valid only under certain conditions: that is, if the zone of water-table fluctuation is a very small percentage of the total saturated depth of the basin, and if the configuration of the water table remains in similar form

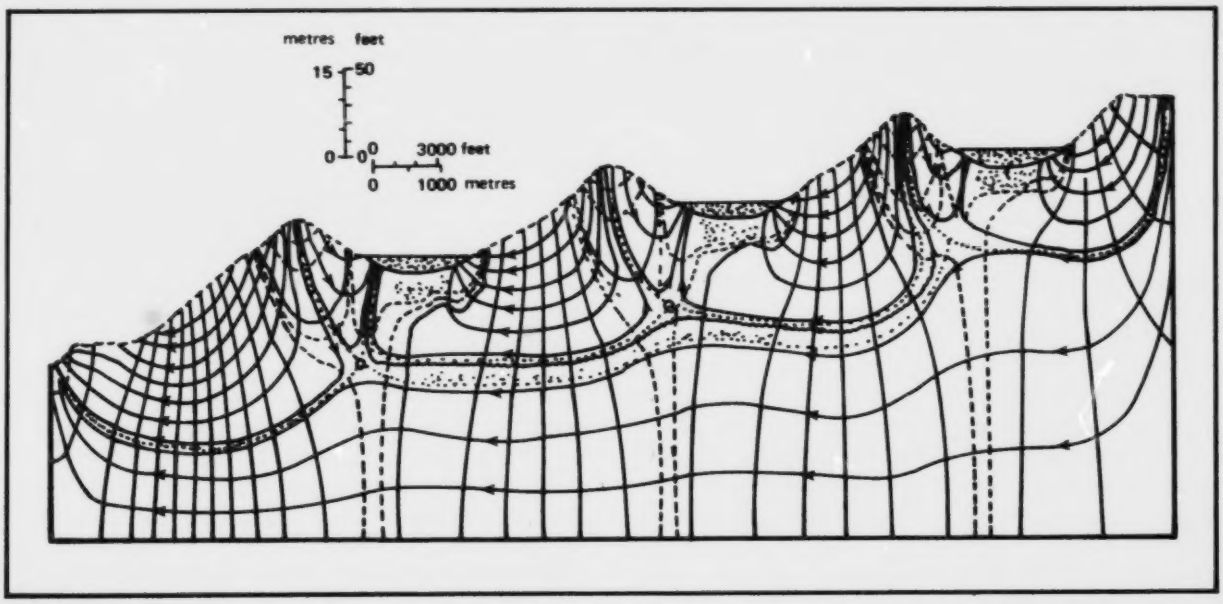



**FIGURE 31.** Hydrologic section showing groundwater flow pattern near lakes in a multiple-lake system (after Winter, 1976).

throughout the period of fluctuation (locations of recharge and discharge remain the same). These two conditions appear to be met in most parts of the Pine Lake basin, at least on an annual basis. Records of water-table fluctuations over a 15-year period are available for three observation wells in the southwestern part of the basin (fig. 3). The maximum recorded annual water level fluctuations were 64 cm (2.1 ft) for a well completed in a surficial sand, 8.5 cm (0.28 ft) in a well completed in till, and 22.6 cm (0.7 ft) for a bedrock observation well.

The second condition listed above may not be met everywhere in the research basin. For example, Meyboom (1966b) showed that, in areas of hummocky topography, local groundwater flow patterns reversed over the year and therefore demonstrated a transient rather than steady-state character. The importance of this process in the Pine Lake area would have to be determined by detailed field studies.

## DISTRIBUTION OF STATIC WATER LEVELS

A piezometric analysis is the most direct method of determining groundwater flow patterns. The static water level for a piezometer open over a small interval represents a discrete measurement of hydraulic head. Water wells may behave in a similar manner if they have been cased down to a specific aquifer where horizontal flow is prominent. When a well has a large open interval, however, the static water level is only a measure of the hydraulic head of the aquifer that has the greatest hydraulic potential in that interval. In an area of upward groundwater flow (a discharge region), the potential increases with depth, so static water levels will be representative of the potential near the bottom of the well, regardless of the length of the open interval. Recharge areas are characterized by a drop in hydraulic head with depth and thus water levels will be under the influence of the shallowest, permeable zone open to the well. In short, knowledge of the general groundwater flow regime and details of well construction are essential to the use of water wells in piezometric analysis.

Unfortunately, the Pine Lake area has no true piezometers from which meaningful hydraulic cross sections could be developed. In addition, the relatively complex stratigraphy and uneven depth distribution of domestic wells in the research basin restrict the use of piezometric surface maps to qualitative investigations. The areal pattern of groundwater flow is illustrated by contouring elevations of non-pumping water levels (fig. 32). This map was constructed from reported static water levels in wells and supplemented from field data on known locations of springs and flowing seismic shot holes. Reference to these data can be found in figure 3 and appendix A.

Figure 32 is neither a piezometric surface map nor a water-table map in that hydraulic heads of different aquifers are present and, at many locations in the basin, hydraulic heads changed with depth. Near the drainage ways and around Pine Lake, static water levels increase with well depth. Exceptions to these trends exist at a few isolated locations. Away from the major ridges and valleys, existing well data suggest that the variation in head with depth tends to be less apparent.

At best, the non-pumping water level map (fig. 32) describes the general direction of groundwater movement. Attempts to derive quantitative information would be pointless. It delineates a groundwater basin where flow is directed from broad recharge areas on the drainage divides and valley flanks to discharge areas near the valley bottom. The greatest proportion of groundwater flux appears to be normal to the drainage way trend. The longitudinal component of flow is relatively small, especially in the basin south of the north end of Pine Lake. Because domestic wells are rarely more than 75 m (250 ft) deep, this water-level map may not represent the flow regime at greater depths.

## QUANTITATIVE EVALUATION OF SUBSURFACE HYDROLOGIC PROPERTIES

Rocks of the Paskapoo Formation are typically soft, semi-consolidated lithologies, so porosity is largely primary. The magnitude of effective porosity depends on the degree of cementation and abundance of clay. Secondary porosity exists in the bedrock strata in the form of fractures and joints, which are the result of post-depositional tectonism and possibly glaciation effects. Fracturing is most conspicuous on examining exposures of the Paskapoo Formation and drillers

commonly log aquifers as "fractured or broken sandstone" or "fractured shale." A clear relationship between stratigraphy and zones of fracturing is not yet established. Jointing also occurs in the surficial deposits (Stalker, 1960) and undoubtedly influences the permeability of the tills in the research basin. Although quantitative specific yield data do not exist for either the bedrock or surficial deposits, a value of 0.1 is probably reasonable for the bedrock strata and most of the drift, except for the surficial sands and gravels where the specific yield is likely about 0.2.

The drilling of water wells over the past 20 years has produced large amounts of shallow, semi-quantitative permeability data. After completing a well, drilling contractors usually conduct a short bail test or pump test to determine well yield. For a domestic well, the period of bailing or pumping is commonly about 30 minutes and the total drawdown is noted. Time-drawdown measurements are rarely taken and observation wells are nonexistent. Occasionally, time-recovery data are recorded and this information has been of value to this study. A few aquifer tests, of several hours duration, also have been performed in the basin. The length of many of these bail or pump tests and accuracy in measurements are probably questionable for proper aquifer testing procedure. All available data, however, were analyzed in order to evaluate the local hydraulic characteristics of the subsurface strata. Measurements of total drawdown (which essentially are specific capacity data) were used to obtain rough estimates of transmissivity through the calculation of "apparent transmissivity" (Farvolden, 1961) which uses the modified nonequilibrium formula (Cooper and Jacob, 1946) and assumes a straight line plot between 0.1 minute and the time of the single observation of total drawdown. The apparent transmissivity either under- or over-estimates the actual transmissivity, depending on whether the drawdown curve flattens or becomes steeper with time. Time-recovery data from bail and pump tests were plotted on semilogarithmic graph paper and transmissivity determined by the straight-line method using the Theis (1935) recovery formula. Time-drawdown data from the longer pump tests were also plotted on semilogarithmic graph paper and the modified nonequilibrium formula (Cooper and Jacob, 1946) was used to calculate transmissivity. Logarithmic plots were made for a few drawdown test data where deviation from the Theis-type curve was evident and in one case where there was data from an observation well. In all, 28 recovery plots and 5 drawdown curves were analyzed.

To present all of the hydraulic test data would be impractical and only three cases will be considered: completion in a sandstone aquifer; a shale aquifer; and a deep well in an interbedded siltstone, shale, and sandstone sequence. The remaining graphs and analyses can be found in appendix D, which also illustrates the hydrogeology of each test location.

Figure 33 shows an example of recovery data from a well completed in a shallow sandstone unit, along the bedrock ridge in the southwestern part of the basin (see fig. 21). Most time-recovery plots (appendix D) show a change in slope during the observations, either as a decrease or as an increase with recovery. These tests were short and may not show whether the changes represent true boundary effects or are a result of well-bore storage. The latest trend of the data was used to determine transmissivity in all tests.

The hydrogeology and results of a 5-hour aquifer test at the north end of Pine Lake are given in figure 34. This well was completed in a shale aquifer that is overlain by clays and sands. In general, the response of the shale is unusual in comparison to tests performed in shale intervals in other parts of the research basin. The reason for this response could be any of the following: fracturing which has greatly enhanced the hydraulic conductivity; induced infiltration with the lake; leakage from the overlying saturated sand layer; or perhaps a combination of the above.

An example of pump test response for a deep well in the extreme northern end of the basin is shown in figure 35. This test was the only one on record where observation well data were also available. Unfortunately, details of well completion were never submitted and drawdown measurements are not of high quality. The drawdown data analyses from the observation well contradict the results of the pumping well. Based on the lithology and results from nearby tests, the transmissivity value determined from the pump-

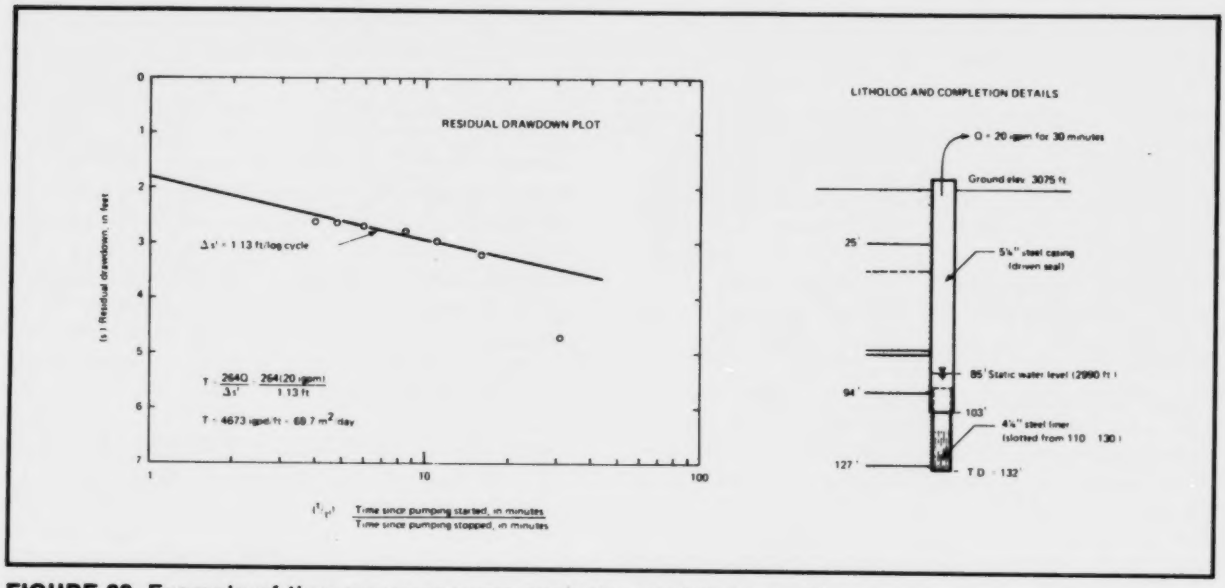

RESIDUAL DRAWDOWN PLOT
Δs' = 1.13 ft/log cycle
T = 2640 / Δs' · 264(20 igpm) / 1.13 ft
T = 4673 igpd/ft = 69.7 m² day
(s') Residual drawdown, in feet
(t/t') Time since pumping started, in minutes / Time since pumping stopped, in minutes
LITHOLOG AND COMPLETION DETAILS
Q = 20 igpm for 30 minutes
Ground elev. 3075 ft
25'
5¼" steel casing (driven seal)
85' Static water level (2990 ft)
94'
103'
4¼" steel liner (slotted from 110 - 130)
127'
T.D. = 132'

**FIGURE 33.** Example of time-recovery curve analysis, sandstone aquifer.

ing well data probably does not represent the strata in this area.

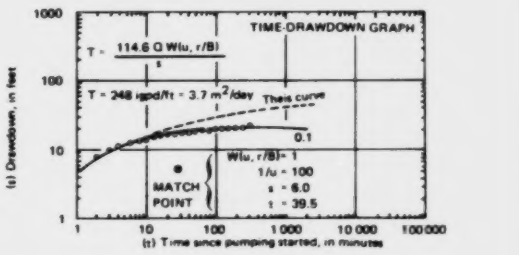
Figure 36, a transmissivity map, summarizes the results of evaluating all drawdown and recovery data in the Pine Lake research basin. Only broad regions of similar transmissivity ranges for the shallow bedrock strata are outlined on the map along with the distribution of the various types of data. Variation in well depth, stratigraphy, and distribution of aquifers is responsible for the complexity of the transmissivity pattern. The map does show that regions of high transmissivity appear to dominate the entire eastern divide and a narrow part of the western ridge, probably because of the major shallow sandstone units as shown in figures 18 to 22. Futher interpretation of the hydrogeologic properties of the various lithologies in the Paskapoo Formation requires a closer examination of individual pump test data and local hydrogeology. Hydraulic conductivities were calculated from the transmissivity data and estimated saturated thicknesses of aquifers in the borehole. This information is tabulated in appendix A.

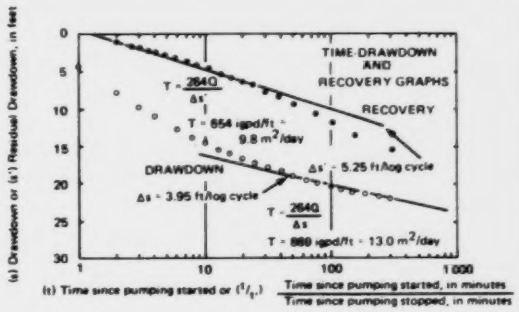
Transmissivities derived from bail or pump tests of sandstone aquifers are commonly in the 30 to 60 m²/day (2000 to 4000 igpd/ft²*) range, although the preliminary data from the ridges in the southern part of the basin indicate that transmissivity can be less than 8 m²/day (500 igpd/ft²). Hydraulic conductivities of sandstone units in the Pine Lake research basin were calculated to be around 0.5 to 25 m/day (10 to 500 igpd/ft²). An average or representative hydraulic conductivity value of these sandstones is probably about 2 m/day (40 igpd/ft²). Higher values may be expected where fracturing is found.

Most wells completed in shale formations are very low producers in the Pine Lake basin, with transmissivities often of less than 1.5 m²/day (100 igpd/ft²), although exceptions are found in competent and fractured shales. Hydraulic conductivity is generally between 0.05 and 0.25 m/day (1 and 5 igpd/ft²) where the shale is soft and therefore tight. Fracturing increases the permeability significantly, so its magnitude can locally exceed those of surrounding sandstones.

Where wells have been completed in a series of strata dominated by siltstone, the yields are intermediate. Transmissivities are generally about 25 m²/day (500 igpd/ft²), although transmissivity could be greater or less depending on the sandstone-shale ratio. On the average, the hydraulic conductivity of siltstones in the

*Imperial gallons per day per square foot





TIME-DRAWDOWN AND RECOVERY GRAPHS
RECOVERY
T = 264Q / Δs'
T = 854 igpd/ft = 9.8 m²/day
DRAWDOWN
Δs' = 5.25 ft/log cycle
Δs = 3.95 ft/log cycle
T = 264Q / Δs
T = 869 igpd/ft = 13.0 m²/day
(s) Drawdown or (s') Residual Drawdown, in feet
(t) Time since pumping started or (t/t') Time since pumping started, in minutes / Time since pumping stopped, in minutes

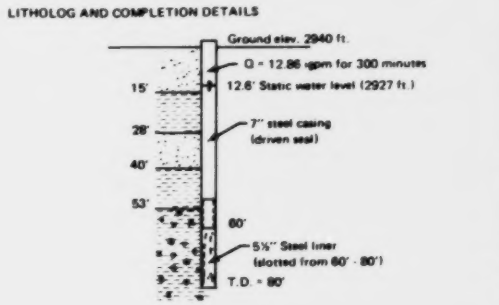
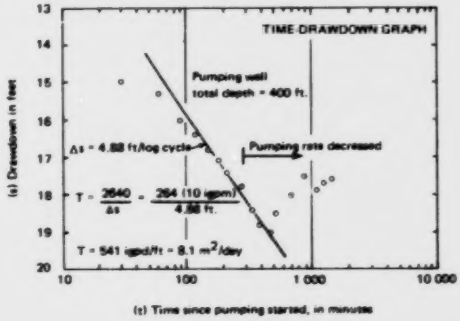
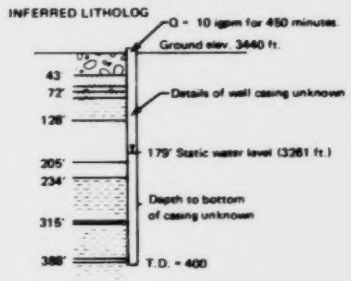



**FIGURE 34.** Time-drawdown graphs and well completion details of a pump test in a shale aquifer.


TIME-DRAWDOWN GRAPH
Pumping well total depth = 400 ft.
Δs = 4.88 ft/log cycle
Pumping rate decreased
T = 2640 / Δs = 264 (10 igpm) / 4.88 ft.
T = 541 igpd/ft = 8.1 m²/day
(s) Drawdown in feet
(t) Time since pumping started, in minutes



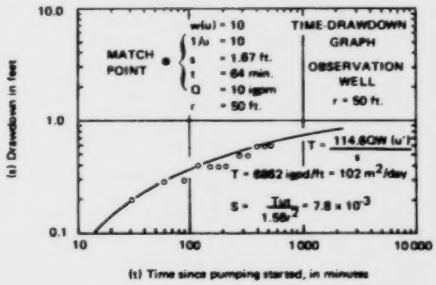


MATCH POINT
w(u) = 10
1/u = 10
s = 1.87 ft.
t = 64 min.
Q = 10 igpm
r = 50 ft.
TIME-DRAWDOWN GRAPH
OBSERVATION WELL
r = 50 ft.
T = 114.6QW(u) / s
T = 6852 igpd/ft = 102 m²/day
S = Tt/r² = 7.8 x 10⁻³
(s) Drawdown in feet
(t) Time since pumping started, in minutes

**FIGURE 35.** Results of a deep well aquifer test in a siltstone-shale-sandstone unit at the northern end of the research basin.

research basin is estimated to be around 0.5 m/day (10 igpd/ft²).

Modern drilling methods virtually eliminated the need to get shallow water supplies from the glacial drift in the Pine Lake area, so permeability data is nearly absent for this material. Two records of shallow wells near Pine Lake can be used to estimate transmissivity of the outwash deposit in which they are completed. Based on the apparent transmissivity of 120 m²/day (8100 igpd/ft²) for a well completed in a 1.2 m (4 ft) thick sand and gravel bed at the north end of Pine Lake, the hydraulic conductivity is estimated to be 100 m/day (2000 igpd/ft²). Similarly, for a shallow well bottomed in a 1.5 m (5 ft) thick bed of sand and gravel outwash west of the lake, the apparent transmissivity was found to be 13 m²/day 860 igpd/ft² and the hydraulic conductivity is estimated to be about 8 m/day (170 igpd/ft²). The absence of more accurate data precludes the appraisal of a representative hydraulic conductivity for these deposits. Data for the till deposits does not exist at all. Taking into account its sandy texture and published figures for tills in western Canada, the hydraulic conductivity of till in the Pine Lake area is estimated to be about $10^{-6}$ to $10^{-2}$ m/day ($10^{-3}$ to 1.0 igpd/ft²), depending on the depth and clay content.

The above evaluation of subsurface hydraulic conductivities has not taken into account the possible anisotropy of the bedrock or surficial aquifers. Without suitable quantitative field data, the degree of anisotropy must be estimated from purely geological considerations or published data from areas of a similar hydrogeologic environment. The stratigraphy and sedimentary character of the basin geology is a good indication that the hydraulic conductivity can be expected to be a tensor rather than scalar quantity where the principal directions are oriented parallel and normal to bedding planes. Freeze (1969a, 1969c) used numerical models of numerous field conditions to show that anisotropy is a dominant characteristic of bedrock strata in western Canada. He found that the anisotropy ratio of horizontal to vertical hydraulic conductivity was usually in the order of magnitude of 10 to 100 for hydrogeologic conditions similar to those found in the Pine Lake area. Gabert (1975) applied an anisotropy ratio of 64 in his electric analogue models of the Red Deer area, immediately north of the Pine Lake basin. Based on these considerations, representative figures for the geologic deposits in the research basin appear to be $K_h/K_v$ = 50 to 100:1 for the Paskapoo Formation; about 10:1 for till; and perhaps 1:1 for the glacial-lake sands and outwash.

The single aquifer test shown in figure 35 is the only quantitative field data available for evaluating the subsurface storage properties in the Pine Lake area. As shown on the logarithmic graph (figure 35), a storage coefficient of $7.8 \times 10^{-3}$ was calculated from the data. Most aquifers in the Paskapoo Formation show some degree of confining conditions in that water levels in wells rise under hydrostatic pressure above the water-bearing zone. The hydraulic conductivities of both the bedrock strata and glacial drift are such that the basin's rock framework is a hydraulically interconnected unit. Tóth (1966b, 1968) and Gabert (1975) arrived at similar conclusions from their hydrogeological studies in south-central Alberta. Under these circumstances, aquifers will react in a semiconfined to confined manner when pump tested, depending on the relative hydraulic conductivities. Confined aquifers are found where higher permeability strata are overlain and underlain by rocks of a much lower permeability. Regionally, it is better to adopt the theory of unconfined flow to describe the occurrence of groundwater or better yet discard the terminology of confined and unconfined as suggested by Freeze (1969c). In any event, the storage coefficients of the Paskapoo Formation can be expected to fall in the $10^{-4}$ to $10^{-2}$ range. The specific yield of shallow bedrock or drift aquifers likely varies between 0.05 and 0.20.

## OCCURRENCE AND DISTRIBUTION OF AQUIFERS

Groundwater flow systems are inherently affected by the distribution of aquifers and the relative hydraulic conductivity contrast with the stratigraphic units. For the various lithologies in the Pine Lake area, the values of hydraulic conductivity listed above basically show which stratigraphic units can be considered the most productive aquifers. For the distribution of these sandstone beds and outwash deposits, see the discussion on geology.

Domestic wells are rarely drilled deeper than 90 m (300 ft) to obtain a suitable supply of groundwater in the Pine Lake area. The most common type of well construction in this region is a small diameter borehole (about 15 cm) which is reamed out to the top of the first significant bedrock aquifer zone, so steel casing can be set with a driven seal. The aquifer interval is usually left as open hole if completed in a competent sandstone, or a torch-slotted liner is installed where caving is encountered (see appendix D for examples). The type and areal distribution of bedrock lithologies, which serve as aquifers to these domestic wells, are shown in figure 37. The term aquifer for the strata in which these wells are completed may be misleading because the water-supply requirement for domestic and stock purposes is usually not greater than 1 $m^3$/day (200 igpd). An obvious feature of the aquifer lithology map is the correlation it has with the distribution of transmissivities. The most productive wells are found in the thicker sandstone units and where bedrock shales are fractured.

Potential sandstone aquifers are well illustrated by the geological sections (fig. 17 to 23). The most extensive proven sandstone aquifer is a shallow unit overlain by siltstone and shale in the western part of the basin, and subcropping below the drift towards the drainage ways. This aquifer is best depicted in section C-C* to F-F* (fig. 19 to 22) where it ranges from about 9 m (30 ft) to over 30 m (100 ft) thick. Unfortunately, permeability data does not exist for many of the deeper, thick sandstones portrayed in the cross-sections. An exception is the very thick sandstone unit as shown in section G-G* (fig. 23). Gabert (1975) bail tested a similar, thick sandstone unit about 8 km (5 mi) northwest of the research basin and evaluated its transmissivity to be around 6 $m^2$/day (4000 igpd/$ft^2$) and the hydraulic conductivity of the water-bearing zones to be equal to 0.3 m/day (6 igpd/$ft^2$). Although this sandstone is stratigraphically equivalent to the unit present in the research basin, its permeability may be different.

On first appearance, the distribution of fracturing (fig. 37) seems to have no definable pattern. Nevertheless, comparing this map with the bedrock topography (fig. 26) shows a number of fractured strata locations along or near the preglacial drainage way. Tóth (1966b) observed the same phenomena in the Olds area of south-central Alberta (Figure 2) and concluded that these fractured zones could be associated with landslides that took place along bedrock channels in preglacial times. In the presence of badland topography, the soft and bentonitic rock types of the Paskapoo Formation would likely be quite prone to sliding near steep valley slopes. Fracturing, present near the drainage divides of the research basin, could be associated with broad, regional folding. Another type of potential fractured aquifer in the Paskapoo Formation are coal seams. According to Vogwill (1979), the hydraulic conductivity of these beds can be quite high, provided the seams are at a depth of less than 45 m (150 ft). Several thin shaly coals are found in the shallow bedrock in the research basin, especially in the shaly sequence around Pine Lake. These thin beds do not constitute significant water-bearing zones.

Most water wells in the Pine Lake area are completed in bedrock in spite of the fact that aquifers exist in the glacial drift. The reasons for this choice are preferences in water quality and ease of well construction. Wells that are completed in the drift are confined to those areas of hummocky moraine and outwash deposits. Adequate supplies of groundwater can be obtained from the till deposits, provided pockets of sand or gravel are present or a permeable avenue exists at the till-bedrock contact. The sands and gravels of the outwash deposits comprise the most promising area for aquifer exploration in the drift.

## HYDROSTRATIGRAPHIC UNITS

Maxey (1964) defined hydrostratigraphic units as "bodies of rock with considerable lateral extent that compose a geologic framework for a reasonably distinct hydrologic system." In order to quantitatively identify hydrostratigraphic units in a geologic environment, such as that found in the Pine Lake basin, a substantial vertical distribution of piezometer and hydraulic conductivity data are required. Except for the "shallow" bedrock strata, little information is available for much of the deeper portions of the research basin's geologic framework. In view of this situation, a qualitative appraisal of hydrostratigraphy is the best that can be currently achieved. Based on the available hydrogeologic data and understanding of the lithostratigraphy, four major

hydrostratigraphic units can be delineated in the Pine Lake research basin. This preliminary assessment will probably be confirmed, discounted, or modified by future hydrogeologic studies.

Hydrostratigraphic unit 1 is assigned to comprise all of the glacial drift deposits because till deposits have significantly different hydraulic properties from the underlying bedrock. This unit has a great control on the unsaturated flow regime and, therefore, rates of recharge to the saturated zone. Furthermore, the groundwater in this unit often has a unique hydrochemistry.

The second unit, hydrostratigraphic unit 2, includes that part of the Paskapoo Formation in which completion of domestic water wells is economical. The thickness of this unit is therefore governed by the maximum likely depth of a domestic well in any given area. On the main ridges, this could range from 90 to 150 m (300 to 500 ft), whereas near the valley bottom it could be less than 60 m (200 ft). Hydrostratigraphic unit 2 is characterized by highly permeable, lenticular and extensive sandstones alternating with lower permeability shales and siltstones. A major sandstone aquifer is found in this unit over most of the research basin. In the longitudinal geological section G-G* (fig. 23), the base of hydrostratigraphic unit 2 could be placed near the top of the deep thick sandstone in the northern part of the basin and the boundary continued south in a manner that splits the massive sandstone in the extreme south end of the basin. This division would be at an arbitrary depth, perhaps 30 m (100 ft) above the Lower Ardley 'B' coal zone (fig. 23).

The two deepest hydrostratigraphic units are for the most part of a conjectural nature. Unit 3 includes that portion of the stratigraphic sequence between the base of the Lower Ardley 'B' coal zone and lower boundary of hydrostratigraphic unit 2. This unit is characterized throughout the basin by its thick extensive sandstones that dominate the strata, with the exception of the area around Pine Lake where it appears to be replaced by a shaly sequence (fig. 20). The hydraulic conductivity of these sandstones may be as great as the shallower beds in unit 2 but their depth usually preclude domestic well development. An exception to this is shown in figure 22. The occurrence and relative depth of this unit is most favorable to the presence of intermediate to regional groundwater flow systems. Water quality, therefore, may be poorer within hydrostratigraphic unit 3.

The deepest unit, hydrostratigraphic unit 4, comprises all rocks below the Lower Ardley 'B' coal zone. This distinction is based entirely on lithological criteria interpreted from electric logs in the study area. The relative absence of sandstone bodies in the Scollard Member (fig. 16) and deeper formations implies that a major regional permeability contrast probably exists between unit 4 and the shallower hydrostratigraphic units. Gabert (1975) and Ceroici (1979) also differentiated a similar hydrostratigraphic boundary, but on the basis of quantitative hydrologic data.

## SURFICIAL EVIDENCE OF GROUNDWATER FLOW PATTERNS

Field mapping of groundwater-generated flow phenomena can be an important method of reconstructing groundwater flow patterns, either in conjunction with measured hydraulic head values or especially in regions where insufficient well data are available. Depending on the local environmental conditions, groundwater flow patterns may be outlined by various physiographic and geologic phenomena which Meyboom (1966a) termed groundwater outcrops. Recharge areas are found to be characterized by a decrease of hydraulic head with depth, topographically elevated areas, abundant dry depressions, relatively thick unsaturated zone, fluctuating water table, well drained soils, variable and lower groundwater temperature, and low total dissolved solids. Groundwater discharge areas are characterized by an increase in hydraulic head with depth, topographically low, general net moisture excess and abundant wet depressions, shallow water table with less fluctuation, flowing wells, springs and seepages, "soap holes", "burnt-crops", abundant growths of phreatophytes, saline soils and salt precipitates, generally warmer and less variable groundwater temperatures, and higher total dissolved solids.

The distribution of flowing domestic wells and reported flowing seismic shotholes (fig. 3 and 4) are noticeably restricted to the valley bottoms in the Pine Lake basin. Most wells are usually less

than 15 m (50 ft) into the bedrock where sandstone and shale aquifers are confined locally by clayey tills. Such is the case for many of the flowing wells drilled near Pine Lake (fig. 4). Buried sand and gravels in outwash deposits will also produce flowing wells along the drainage ways where they are locally confined by clays. Both the increasing hydraulic head with depth environment and locally confining conditions are probably responsible for flowing wells. Free-flowing yields are usually less than 0.2 L/s (3 igpm), but they can exceed 3.8 L/s (50 igpm), as at the north end of Pine Lake where shallow sandstones and fractured shales are confined by clays in the glacial drift.

Springs and seepages are quite numerous in the Pine Lake research basin. Rarely does the flow of these springs exceed 0.8 to 1.2 L/s (10 to 15 igpm). An exception to this was found in the sinuous, narrow valley north of Pine Lake (location 11-3, fig. 4) where the flow rate was estimated around 2.7 L/s (35 igpm). Most springs in the basin discharge at rates between 0.1 to 0.4 L/s (1 to 5 igpm). The geologic nature of these features is often difficult to ascertain because vegetation and the glacial drift obscure the situation. Many of these springs have been dug out and cribbed off. The broad areas of seepage along drainage bottoms and springs found along slopes of hills probably indicate upward-rising groundwater flow and shallow water-table conditions in rather homogeneous, low permeability geologic materials. Some larger springs are usually found in valley bottoms near the base of a steep slope. These springs are almost entirely of the contact type, either as a result of permeable sandstone overlying a shale sequence in areas of thin drift or where coarse outwash deposits overlie clayey till. Many springs are further localized by slumping of surficial materials along steep valley walls. At several of the bigger spring locations, "springy," mound-type features are common, although they are not quite the same as the "soap holes" or "mud springs" described by Tóth (1966a).

The saline soil association along the Ghostpine Creek drainage system (Bowers, Peters, and Newton, 1951) was verified by observations of salt precipitates in this area. According to Tóth (1966a), these salt precipitates consist of sodium sulfate, calcium and magnesium sulfates, and sodium bicarbonates in varying amounts. The salts, in association with springs, flowing wells, saline sloughs, and a shallow water table confirm the result of the evaporation of upward-rising groundwater. The microclimate and abundance of surface water in the northern part of the research basin appears to exclude the development of salt precipitates in discharge areas of this region.

Figure 38 summarizes the results of the field observations and their interpretation in the context of regional groundwater flow and shows that Pine Lake, Ghostpine Creek, and their associated tributaries are major discharge areas for groundwater flow in the Pine Lake research basin.

## CONCEPTUAL MODEL OF GROUNDWATER FLOW

On the basis of the available geologic data, nonpumping water levels, subsurface hydrologic properties, field evidence of groundwater discharge, and theoretical considerations, it is not a difficult task to formally conceptualize the groundwater flow patterns in the Pine Lake research basin. The groundwater regime in the Pine Lake area is characterized by a three-dimensional, heterogeneous, anisotropic unit or groundwater basin, as in the context defined by Freeze and Witherspoon (1967). A suitable two-dimensional section through a groundwater basin is representative of the flow patterns, provided it is taken parallel to the direction of maximum hydraulic gradient. In the case of the Pine Lake area, a representative section could include any line transverse to the major drainage ways, assuming that the component of regional groundwater flow longitudinal to the basin is negligible in comparison to the lateral component.

The general pattern of groundwater flow (fig. 39) appears to be fairly simple. Groundwater recharge is most pronounced along the main ridges where the flow is essentially vertical through low permeability glacial drift and siltstone-shale strata. Relatively thin sandstones of greater hydraulic conductivity interrupt the vertical flow regime and serve to transmit the water horizontally to areas of local and intermediate groundwater discharge. A number of local flow systems are found, especially where the water table configuration is irregular as in the hummocky terrain on the

west side of the basin. Flowlines are refracted substantially on encountering the extensive, shallow sandstone unit in hydrostratigraphic unit 2. This sandstone unit plays an important role in an intermediate-type flow system that together with the local flow systems is responsible for much of the groundwater discharge in the Pine Lake basin. Regional groundwater flow continues downward to the deep, thick sandstone sequence in hydrostratigraphic unit 3. From here, groundwater movement is lateral through the thick sandstones which transmit water from the regional recharge areas in the uplands to the major discharge areas around Pine Lake. Below hydrostratigraphic unit 3, groundwater flow is dominated by a west to east motion that is part of a much larger regional flow system (in the thick Horseshoe Canyon Formation) discharging towards the Red Deer River.

Two features of the groundwater flow patterns cannot be adequately illustrated by the scale of figure 39. One of these is the local pattern of flow associated with Pine Lake. Regionally, it appears to act as a major discharge feature, but locally the situation may be more complex. Although the models of Winter (1976, 1978) do not seem to apply in the regional pattern, they may offer insight into local groundwater flow-lake interaction. A second area where the flow pattern is not properly represented by the regional model (fig. 39) is in the areas of hummocky moraine. This feature is also likely to be complicated by local flow systems. The diagram of Winter (1976) in figure 31 probably represents the type of flow patterns existing in the knob-kettle topography prominent in the northern and western parts of the research basin. Highly developed local systems between sloughs are an integral part of an intermediate and regional system. Even this picture might be over-simplified by the fact that Meyboom (1966b) documented a sequence of transient flow conditions where directions of groundwater flow reversed on an annual basis.

## QUANTITATIVE MODEL OF GROUNDWATER FLOW

Finite-difference and finite-element programs were used to obtain quantitative models of the groundwater flow pattern in the Pine Lake basin. Numerical methods are well documented in the hydrologic literature and therefore the theory behind them will not be presented. Remson, Hornberger, and Molz (1971) present an introductory treatment of these subjects, and Pinder and Gray (1977) offer a more advanced dissertation.

For the purpose of this preliminary study, only a very simple analysis was undertaken. The governing equation of groundwater flow for heterogeneous - anisotropic media and steady-state flow is given by

$$\nabla \cdot ( K \nabla h) = 0 \qquad (1)$$

where h is the hydraulic head and K is the hydraulic conductivity tensor, which in two dimensions is written as

$$K = \begin{bmatrix} Kxx & Kxz \\ Kzx & Kzz \end{bmatrix}$$

Equation (1) is solved numerically for the hydraulic head and these data can be contoured by the computer to produce a quantitative flow net.

Figure 40 shows an example of a finite element simulation along cross section C-C*. Making the hydraulic conductivity of the sandstone units forty times greater than the conductivity of the mudstones and using an anisotropy ratio of 44:1 produced the best qualitative fit with the conceptual field model. Note should be made that the results shown in figure 40 have been plotted as a transformed section in order to properly account for anisotropy (Freeze and Cherry, 1979). Many more simulations of this type and piezometric data will be needed to justify the validity of this model. For now, it should be viewed as a starting point for future numerical studies of the Pine Lake basin.

## HYDROGEOCHEMISTRY

Over 200 chemical analyses of well waters, springs, and surface water in the Pine Lake area were examined. Approximately half were pre-existing records of samples submitted to local health authorities by private well owners over the past 20 years. The units of measurement for these

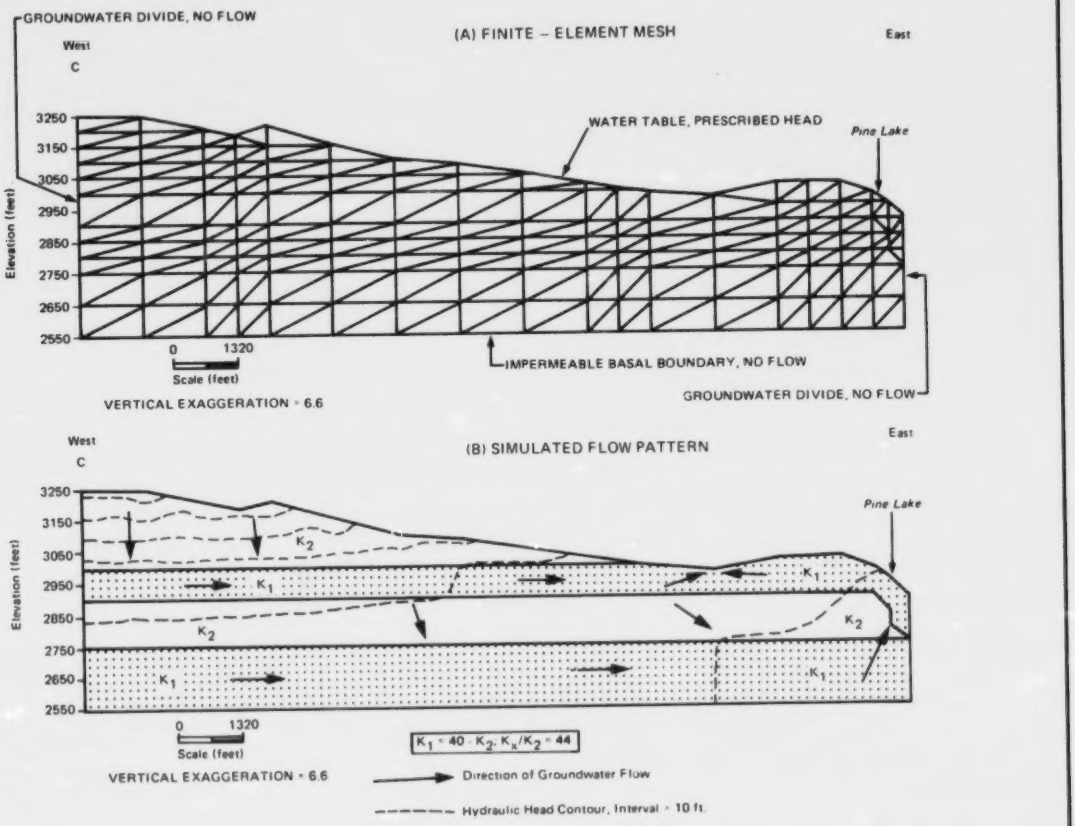



**FIGURE 40.** Finite element simulation along cross section C-C*, Pine Lake research basin.

analyses are usually parts per million (ppm) or milligrams per litre (mg/L), with grains per gallon used in some older records. Appendix B gives the conversion of this data to equivalents per million (epm) and their respective percentages. The other half of the hydrochemistry data were detailed analyses of water samples from a field survey. These samples were analyzed by the Alberta Research Council Geochemistry Laboratory. The results are also presented in appendix B. Interpreting groundwater chemistry from many of the well samples tabulated in appendix B must be done carefully. In many cases, construction details are unreported and the sampling procedures used by private well owners is often questionable. Nevertheless, for this study, the volume of data and its consistency is sufficient to make general observations on the hydrochemical patterns inferred from the available data distribution (figs. 3 and 4).

## CHEMICAL TYPE OR FACIES OF GROUNDWATER

Figures 41 and 42 (trilinear plots of the type proposed by Piper, 1944), show the hydrochemistry of water wells, springs, and a few surface bodies in the Pine Lake area. Because only a few wells in the entire basin are known to be completed in the glacial drift, a Piper diagram for drift wells was not constructed. It is hoped

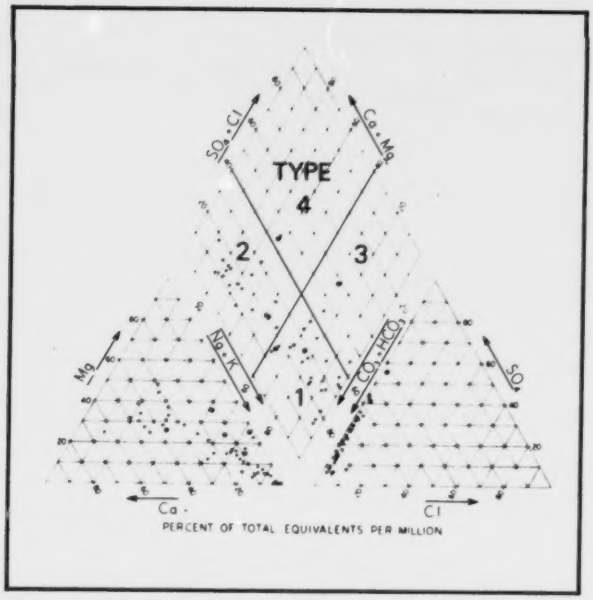



**FIGURE 41.** Piper trilinear diagram of spring and surface water samples, Pine Lake research basin.

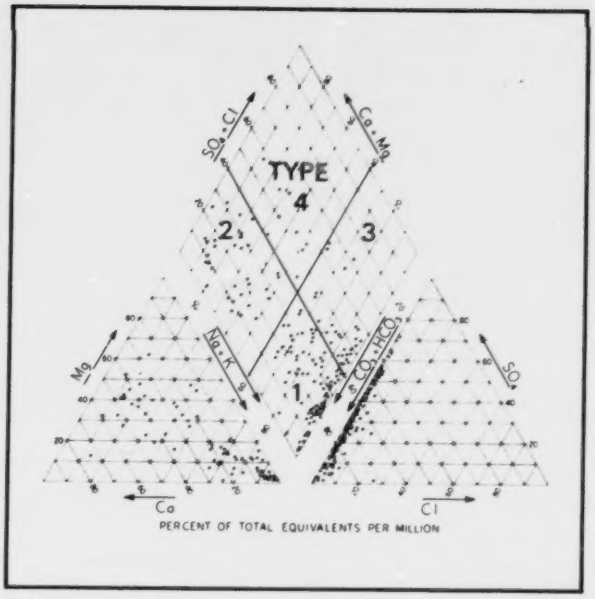



**FIGURE 42.** Piper trilinear diagram of groundwater samples from water wells, Pine Lake research basin.

that any unique chemistry of groundwater in the drift will be reflected by the analyses of spring waters.

The concept of hydrochemical facies or types introduced by Back (1966) provides an efficient method of evaluating the relationships between groundwater chemistry and those factors that control its character (geology, topography, climate, and groundwater flow). The chemical facies of waters in the Pine Lake basin have been classified on the trilinear plots according to the dominant cations and anions in the water. Boundaries have been arbitrarily chosen at the 60 percent value of equivalents per million for $Na^+ + K^+$ and $HCO_3 + CO_3^{2-}$. Four types of groundwater have been delineated and are numbered on the diagrams in order of their apparent abundance of occurrence. Type 1 is defined as a sodium-bicarbonate facies, Type 2 as a calcium-magnesium-bicarbonate water, Type 3 as a sodium-sulfate-bicarbonate water, and Type 4 as a calcium-magnesium-sulfate-bicarbonate facies. This classification is consistent with that of Gabert (1975), who used over 400 analyses in determining the hydrochemical facies of a large region north of the research basin.

## DISTRIBUTION OF HYDROCHEMICAL FACIES

Figure 43 shows the areal distribution of hydrochemical facies in the research basin according to the classification above. Both spring and well data are plotted on this map for a composite representation of the chemistry of groundwater in the shallow bedrock and drift. Hydrochemical cross sections have not been constructed because of the insufficient vertical distribution of data.

As shown on the facies map (fig. 43), type 1 (sodium-bicarbonate) groundwater is the most common hydrochemical facies encountered in the Pine Lake research basin. Its broad distribution does not appear to be topographically controlled nor is it unique to springs or wells. One significant observation is that it is almost always the type of water encountered in deep aquifers.

Type 2 (calcium-magesium-bicarbonate) waters are the next most abundant in the basin. They are most conspicuous in a region enveloping the east side of Pine Lake and extending southeasterly along the flank of the eastern drainage divide. The type 2 facies is also prominent as discontinuous

patches near type 3 waters along both drainage divides. No correlation can be made with topography and the occurrence of this facies. Type 2 groundwater is probably a shallow phenomenon because calcium-magnesium-bicarbonate types are frequently found in springs, and wells producing this water are usually less than 30 m (100 ft) deep.

Water dominated by sodium-sulfate-bicarbonate (type 3) is found in an area adjacent to the entire eastern drainage divide and in an irregularly shaped region in the southwestern part of the basin. A few isolated occurrences are found near Pine Lake and Ghostpine Creek; and only one spring in the basin contained a type 3 facies. The majority of wells completed in this facies are between the depths of 30 to 65 m (100 to 215 ft), although about 25 percent of the total are less than 30 m (100 ft) deep.

Type 4 (calcium-magnesium-sulfate-bicarbonate) is the least common hydrochemical facies and is restricted to the major bedrock ridges in the extreme southern part of the research basin. Two isolated sample points are present on elevated ridges in the western part of the study area. Wells in this facies range from around 35 to 80 m (120 to 270 ft) deep. One analysis of a spring (fig. 41) near the edge of a steep bedrock ridge also yielded a type 4 water. A significant characteristic of type 4 waters is that total dissolved solids is always greater than 1000 mg/L (appendix B).

Surface water was not systematically sampled in the Pine Lake basin. The chemistry of the few surface water samples is shown in figure 41, where the appropriate hydrochemical facies is also indicated. Water from the lower reaches of Ghostpine Creek is of the type 1 facies group. In these analyses, TDS range from 500 to 700 mg/L. In comparison, values of 475 mg/L and 500 mg/L were estimated for the TDS content of Pine Lake and the upper reach of Ghostpine Creek, respectively. Analyses of three sloughs in the southern area of the basin were plotted in separate facies, yielding TDS values varying from less than 500 mg/L to over 2500 mg/L.

## DISTRIBUTION OF CHEMICAL CONSTITUENTS

In an attempt to further evaluate the hydrogeochemistry in the Pine Lake area, contour maps of various chemical constituents were prepared. These maps, however, showed very little new information over the hydrochemical facies map or correlation with the inferred groundwater flow patterns. For practical purposes, only the distribution of TDS will be described. The spatial variation in TDS is illustrated in figure 44 by a contour interval equal to 500 mg/L. Groundwater in the Pine Lake basin has a dissolved solids value of 1000 mg/L or less. It rarely exceeds 2000 mg/L in the shallow hydrostratigraphic units. The most significant hydrochemical trend displayed by this map is that mineralization of groundwater is highest along the drainage divides and lowest towards lower elevations. The freshest subsurface water (less than 500 mg/L) is found in a region enveloping Pine Lake. Water with concentrations greater than 1000 mg/L dominate the entire eastern ridge, the highly elevated northern upland, and a broad mid-slope region that extends from the southwestern shore of Pine Lake to the southern edge of the basin in Township 35, Range 24. Except for a few isolated areas, most of the western drainage ridge is relatively low in TDS in comparison to its eastern counterpart. Anomalously high TDS concentrations (greater than 2000 mg/L are found in an area of hummocky moraine in the northeastern part of the basin and on a bedrock ridge at the southern extremity. Neither of these high TDS wells is very deep; both are less than 60 m (200 ft).

## INTERPRETATION OF HYDROCHEMISTRY

A lot of research has been devoted to the use of the chemical composition of groundwater as an interpretive tool in hydrogeological studies. Various authors laid the foundation of this theory. They sought to show how groundwater chemical types could be attributed to groundwater flow and the hydrogeologic environment. For example, according to the theory of Chebotarev (1955), one should see the following regional changes in dominant anions with distance and age:

$$HCO_3^- \rightarrow (HCO_3 + SO_4^{2-}) \rightarrow (SO_4^{2-} + Cl^-) \rightarrow Cl^- \quad (2)$$

This sequence implies groundwater should naturally evolve from a bicarbonate type in recharge areas to domination by sulfate or chloride ions in discharge areas, depending on the scale of the flow systems involved.

Based on the interpretation of the groundwater flow patterns in the last section and the hydrochemical facies map (fig. 43), an attempt can be made to link various facies types, and therefore individual chemical constituents, with areas of recharge and discharge and particular flow systems. Unfortunately, the influence of flow patterns is not strongly developed in the hydrochemical facies of the Pine Lake research basin. The concentrations of chemical constituents are probably more strongly modified from their principal concentrations by changing mineralogy, cation exchange processes, bacterial action and mixing phenomena than can be attributed to the classical Chebotarev sequence and the concept of flow systems.

Type 1 (sodium-bicarbonate) groundwaters are dominant throughout the Pine Lake area and undoubtedly represent the facies which characterizes the entire basin and upon which the other facies are superimposed. The apparent recharge areas in the hummocky moraine on the upland areas have diverse chemistries. Whether this is a result of actual areal variation in hydrochemical facies or more reflective of variable well depth is difficult to ascertain. In recharge areas, one should expect low TDS and high concentrations of bicarbonate. The reason is that groundwater acquires its principal chemical composition during infiltration into the soil and, because the environment is rich in $CO_2$, $HCO_3^-$ is the most abundant species through dissolution of carbonates as follows (Davis and De Wiest 1966):

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^- \quad (3)$$

$$HCO_3^- \rightarrow H^+ + CO_3^{2-} \quad (4)$$

$$CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^- \quad (5)$$

Discharge areas should be characterized by higher total dissolved solids and possibly domination of the anions by $SO_4^{2-}$, at least according to the Chebotarev sequence. The absence of sulfate or even sulfate-bicarbonate in the discharge area is readily apparent on the hydrochemical facies map. Clearly, the hydrochemical patterns in the Pine Lake basin do not conform to the Chebotarev sequence. Type 1 and 2 waters appear to be prominent in the recharge areas but they also characterize the mapped discharge areas around Pine Lake and Ghostpine Creek. The noticeable decrease in TDS towards these drainage ways completely disagrees with the conceptualized flow patterns. Because deeper wells are constructed along the ridges, the high TDS values in these areas are inevitably explainable for this reason alone. The distribution of type 3 (sodium-sulfate-bicarbonate) and type 4 (calcium-magnesium-sulfate-bicarbonate) groundwaters are largely restricted to mid-slope position of ridges and along the southern boundary of the basin. Some of these occurrences may be associated with local or intermediate flow systems, but they are probably controlled by local mineralogical and hydrochemical conditions. The presence of an extensive area of type 4 waters on the southern sandstone probably is a result of the highly permeable nature of the strata which reflects the chemical character of the glacial drift and shallow bedrock superimposed on the regional sodium-bicarbonate water at depth.

The limited amount of data makes it difficult to delineate unique hydrochemical facies for each hydrostratigraphic unit, especially from the maps presented earlier which contain data from wells of variable depth and springs. Furthermore, since very few wells produce groundwater from the drift deposits, the areal chemistry of this unit is not represented on the hydrochemical maps. Most domestic wells are completed in the shallow bedrock for the simple reason that drift waters are very hard and therefore are typically dominated by $Ca^{2+}$ and $Mg^{2+}$ as major cations and $HCO_3$ as the major anion, although $SO_4^{2-}$ may be present if sufficient soluble sulfate minerals exist in the till. Ca-Mg-$HCO_3$ or Ca-Mg-$SO_4$-$HCO_3$ waters characterize the glacial deposits whereas Na-$HCO_3$ waters dominate in the bedrock (especially at depth).

The complex mineralogical assemblages which occur in the glacial drift deposits of the Pine Lake area are attributable to generation of the prominent anions and cations. As noted above, the dissolution of carbonate minerals and soil zone $CO_2$ is primarily responsible for the abundance of $HCO_3$ in shallow groundwaters. The abundance of calcareous materials in the tills and other deposits of the area are sufficient to account for the prominence of Ca-Mg-$HCO_3$ waters in the drift. Wallick (1977) also suggested that weathering of

silicate minerals may contribute to the overall concentrations of these ions and others but recognized that carbonate equilibria is the most important control on the solubilities of $Ca^{2+}$, $Mg^{2+}$, $CO_3^{2-}$ and frequently $Fe^{2+}$.

Gypsum and other sulfates also occur in drift materials and their dissolution almost always is responsible for any significant concentrations of $SO_4^{2-}$ in drift waters. The dissolution reaction for gypsum is represented by:

$$CaSO_4 \cdot 2H_2O \rightarrow Ca^{2+} + SO_4^{2-} + 2H_2O \quad (6)$$

In many parts of the research basin, the presence of extensive outwash deposits in the drift have precluded the concentration of $SO_4^{2-}$. A possible reason for this is that the strong flushing effect of local flow systems could have removed much of the soluble sulfates from the flow regime. The abundance of sulfates in shallow groundwater along the southern boundary of the research basin may be a function of the effects of higher evaporation losses in this area. As the leaching depth is shallow, small amounts of gypsiferous or pyritic material in the drift or bedrock may be a significant source of $SO_4^{2-}$ and $Ca^{2+}$. The relative abundance of $SO_4^{2-}$ in groundwaters along the eastern divide is problematic but may be due to the composition and thickness of tills.

Moderate concentrations of sodium in drift waters could be acquired through the processes of cation exchange on montmorillonitic clays, but the majority of Na-$HCO_3$ spring waters issuing from drift deposits around Pine Lake, Ghostpine Creek and their tributaries are probably the result of the strong influence of chemical processes dominant in the bedrock strata. These springs, therefore, are acting as inliers of bedrock hydrochemical facies rather than reflecting hydrochemical patterns in the drift.

The chemistry of groundwater encountered in the bedrock (Paskapoo Formation) of the Pine Lake area is highly dependent on the hydrogeochemistry of the glacial drift. Exceptions to this interpretation occur in the deep groundwater systems and some of the discharge areas. All have evolved, however, from shallow calcium-magnesium-bicarbonate waters in the glacial drift to a predominantly sodium-bicarbonate facies in the bedrock. Dissolution of carbonates, sulfates and other minerals still influence the concentrations of the dominant anions and cations in bedrock groundwaters, but more important now are the roles of other geochemical processes which greatly modify the primary chemical composition acquired in shallower zones. Freeze and Cherry (1979) identified four major processes: cation exchange, $CO_2$ generation at depths far below the water table, sulfate reduction, and oxidation of sulfide minerals.

The most likely explanation for the dominance of sodium-bicarbonate waters in the bedrock of the Pine Lake research basin is the process of cation exchange coupled with carbonate dissolution. The abundance of bentonite (for example, montmorillonite) in the rocks of the Paskapoo Formation provides ample opportunity for the replacement of $Na^+$ exchange sites by $Ca^{2+}$ which is adsorbed on the clays. This process also enhances further calcite dissolution which, if maintained at low concentrations, keeps equilibrium $HCO_3^-$ concentrations high (Freeze and Cherry, 1979). High bicarbonate concentrations can also result from sulfate reduction by oxidation of organic matter thereby generating $CO_2$ at depth as follows:

$$2CH_2O + SO_4^{2-} \rightarrow HCO_3^- + HS^- + CO_2 + H_2O \quad (7)$$

This process requires an anaerobic bacteria (Hem, 1970) and is often identifiable in wells by the odor of $H_2S$ gas. Occurrences of this phenomenon in the research basin are known and therefore biochemical sulfate reduction is a likely process for explaining the absence or low concentrations of $SO_4^{2-}$ in many parts of the basin.

Two minor geochemical processes which are associated with carbonaceous strata in the subsurface may occur in the Pine Lake area. First, increased concentrations of $HCO_3$ may also be expected in coal-bearing strata due to greater amounts of $CO_2$. A final geochemical process which should be mentioned is the possibility of the oxidation of sulfide minerals. The presence of pyrite in coals and carbonaceous shales in the Pine Lake area is documented by a number of detailed coal exploration geologic logs (fig. 5). According to Freeze and Cherry (1979), hydrogen ions are released as a result of the reaction:

$$FeS_2 + (15/4)\,O_2 + (7/2)\,H_2O$$

$$\rightarrow Fe(OH)_3 + 4H^+ + 2SO_4^{2-} \qquad (8)$$

This oxidation must occur in the unsaturated zone and from the high production of $H^+$ a high $HCO_3^-$ content can be maintained in high pH groundwaters. Note should be made that significant amounts of $SO_4^{2-}$ is also generated and that this process can be active in drift materials derived from pyritic strata.

## WATER QUALITY CONSIDERATIONS

The quality of water in the Pine Lake area can be interpreted from the maps showing the hydrochemistry (figs. 43 and 44) of the basin. All groundwaters sampled in the research basin appear to be suitable for human and livestock consumption, although some of the constituents exceed recommended drinking water standards set by the U.S. Environmental Protection Agency (1975). Quality of bedrock waters is generally superior to that of shallow drift wells because of its softer nature. The high sodium content and TDS of most of the groundwater in the basin limit its use in irrigation.

## GROUNDWATER RESOURCES

Hydrogeologic investigations are incomplete without an evaluation of the groundwater resources. In groundwater exploration and development, this involves identifying and mapping major aquifers, determining quantitative hydrologic properties through aquifer testing, and predicting sustainable well yields based on the hydraulic data. For the design of a particular groundwater development, this analysis would also include an assessment of the possible impact on the existing groundwater regime. More important, however, in the context of the objective of establishing the Pine Lake research basin, is an evaluation of the subsurface components of the hydrologic cycle with emphasis on parameters such as recharge, discharge, and natural basin yield.

## GROUNDWATER PROBABILITY

Figure 45 is a groundwater probability map of the research basin. "Groundwater probability" may be misleading in that figure 45 does not actually represent expected aquifer yields, but rather the anticipated range of yields for wells completed in the shallow bedrock, according to standard well-construction practices in the area.

Tóth (1966b) introduced the concept of the 20-year well yield ($Q_{20}$) through adaptation of the modified nonequilibrium formula (Cooper and Jacob, 1946) to arrive at the following equation:

$$Q_{20} = \frac{T\,H}{c} \qquad (9)$$

where T = transmissivity, H = total available drawdown between static water level and the top of the aquifer zone, $Q_{20}$ = maximum flow rate that can be sustained over 20 years without drawdown below the top of the main aquifer penetrated by the well, and c = conversion factor to account for 8 cycles of time and consistency of units. The predictive accuracy of this calculation depends greatly on how representative the transmissivity value is of regional conditions. Nevertheless, this concept has been widely employed in Alberta and for purposes of consistency equation (9) has been used to produce the numerical values given in figure 45. The type of transmissivity data from which the yield points were calculated is also indicated on the map, and values of 20-year yield, transmissivity, and available drawdown are tabulated in appendix B. The complex stratigraphy and shortage of good aquifer tests prevents a detailed analysis of aquifer yield in the Pine Lake basin, and therefore only three yield ranges have been mapped: 0.1 to 0.4 L/s (1 to 5 igpm); 0.4 to 1.9 L/s (5 to 25 igpm); and greater than 1.9 L/s (25 igpm). Higher yields are widespread but differentiating them is not warranted until further pump test data are available.

The well-yield pattern in figure 45 reflects both transmissivity and water level parameters. In most parts of the basin, shallow bedrock wells can be expected to have sustained safe yields in the 0.4 to 1.9 L/s (5 to 25 igpm) range. Areas of well yield less than 0.4 L/s (5 igpm) are widespread on the western and southern ridges where poor well construction, deep static water levels, and low transmissivities are probably responsible for the existing poor yields. Wells capable of sustaining yields of 1.9 L/s (25 igpm) are found along most of

are found along most of the eastern divide, near the north end of Pine Lake, and along a narrow bank just east of the western ridge. Except for a few of the wells completed in fractured shale, most produce from major sandstone aquifers. Based on the available data, sustainable 20-year well yields may exceed 7.50 L/s (100 igpm) for parts of the shallow sandstone aquifers. Where they are sufficiently thick and the hydraulic conductivity enhanced by fracturing, $Q_{20}$ values could be even greater as suggested by some of the anomalously high values.

## GROUNDWATER EXPLORATION

It was recognized early in the hydrogeologic evaluation that there were many parts of the research basin where geologic and quantitive hydrologic data were lacking, especially at depths exceeding those of domestic wells. A small exploration program was undertaken during the summer of 1979 to substantiate the hydrogeology as inferred from geophysical data. This program consisted of drilling testholes at four different locations in the Pine Lake research basin. Lithologic samples were taken at regular intervals and all four holes were electric logged. After well completion, aquifer tests of several hours duration were conducted at each site and water samples obtained for chemical analysis. These four wells have been capped but will possibly be integrated into a more extensive piezometer network in the near future.

### Testhole PL79 - 1: (14-23-35-24-W4)

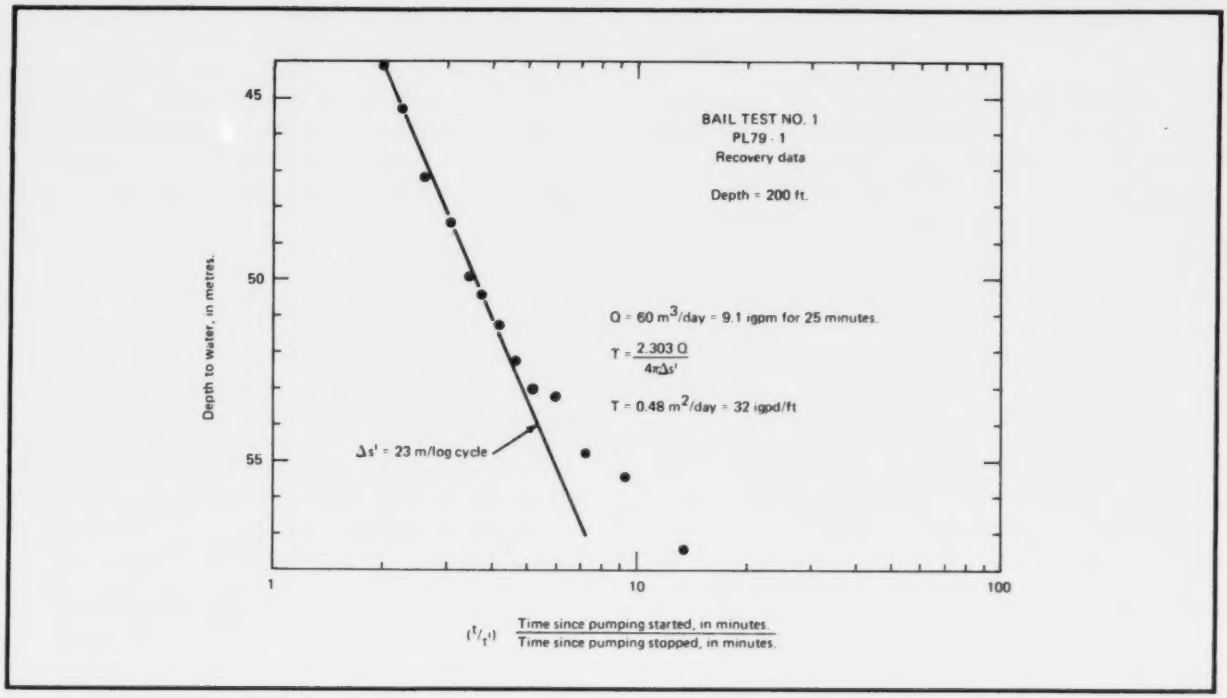
The location of this site was chosen for its representation of the hydrogeologic environment in the southeastern part of the research basin. Drilling to a depth of 116 m (382 ft) by cable-tool rig confirmed the presence of a massive sandstone unit which previously was inferred from geophysical data (fig. 22). The geologic results and well construction of this testhole are graphically shown in figure 46. Cable-tool drilling delineated three major zones of high hydraulic conductivity: 42.7 to 45.8 m (140 to 150 ft); 73.8 to 77.4 m (242 to 254 ft); and 108.2 to 115.2 m (353 to 378 ft). Depth to static water level dropped only slightly with depth but as drilling proceeded into the deep sandstone unit (fig. 46) water levels dropped substantially (more than a metre). Three short bail tests were conducted during drilling of the testhole, after attaining depths of 60 m (200 ft), 90 m (300 ft), and 116 m (382 ft). Interpretation of recovery levels from the bail tests is given in figure 47. The results of these tests are not adequate to quantify the vertical distribution of hydraulic conductivity. Drawdown data from a 12-hour aquifer test are shown in figure 48. Evaluation of this data by the straight-line method yielded a transmissivity value of 60 $m^2$/day (4020 igpd/$ft^2$) for the total estimated thickness of saturated sandstone at the site. Water chemistry analyses of well samples showed the most significant change at a depth of 49 m (160 ft), above which TDS is around 500 mg/L and groundwater is of the Na-$SO_4$-$HCO_3$ type. Sampling of groundwater below the shallow aquifer indicated that the Na-$HCO_3$ facies was dominant and that the TDS were around 850 mg/L.

### Testhole PL79 - 2: (8-18-36-24-W4)

This particular testhole site was chosen because of the general absence of hydrogeologic data in the area and good central location. Although a thick shallow sandstone unit was expected to be encountered, the main object of this exploration project was to pump test in much deeper zones. The testhole was rotary drilled to a total depth of 134 m (440 ft) with 6 in steel casing installed to 86 m (282 ft) and the rest of the hole left open. Exploration data from this site are given in figure 49. Except for the basal several feet of the thick shallow sandstone, no aquifer zones were encountered in the entire section, which was dominated by shale and siltstone with minor showings of coal. The results of a 6-hour pump test on this testhole are shown in figure 50. Transmissivity was calculated to be 0.4 $m^2$/day. A water sample taken during the pump test was analyzed as 662 mg/L for TDS and classified as an Na-$HCO_3$ type groundwater.

### Testhole PL79 - 3: (4-26-36-25-W4)

The stratigraphic data determined from the PL79-3 testhole concurred exactly with the geology inferred from nearby structure testhole electric logs. Figure 51 shows the strip lithologic log, electric logs, and construction details of this exploratory hole. A rotary rig was used to bottom the hole in a thick deep sandstone unit, 113 m (371 ft) below the land surface. Great difficulty in well construction was encountered due to a loss of cir-


BAIL TEST NO. 1
PL79 - 1
Recovery data
Depth = 200 ft.
Q = 60 m³/day = 9.1 igpm for 25 minutes.
T = 2.303 Q / 4πΔs'
T = 0.48 m²/day = 32 igpd/ft
Δs' = 23 m/log cycle
Depth to water, in metres.
45
50
55
1
10
100
(t/t') Time since pumping started, in minutes. / Time since pumping stopped, in minutes.

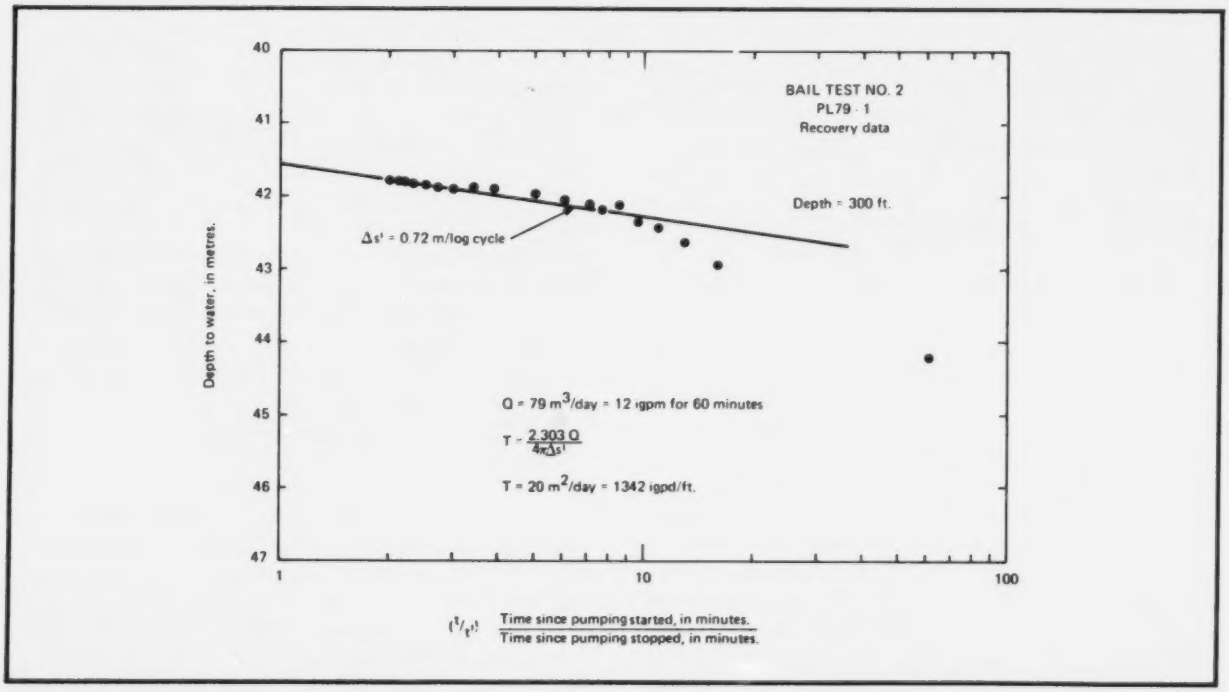



**FIGURE 47.** Bail-test data, PL79-1.

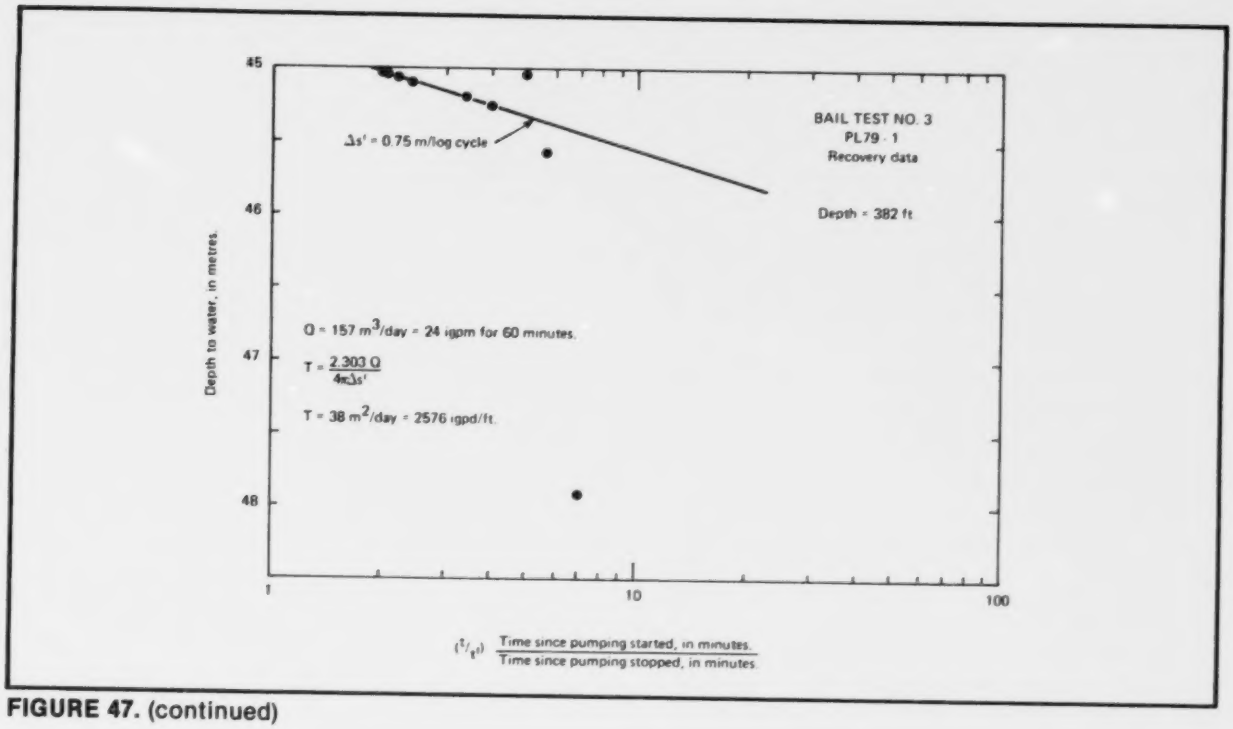



**FIGURE 47.** (continued)

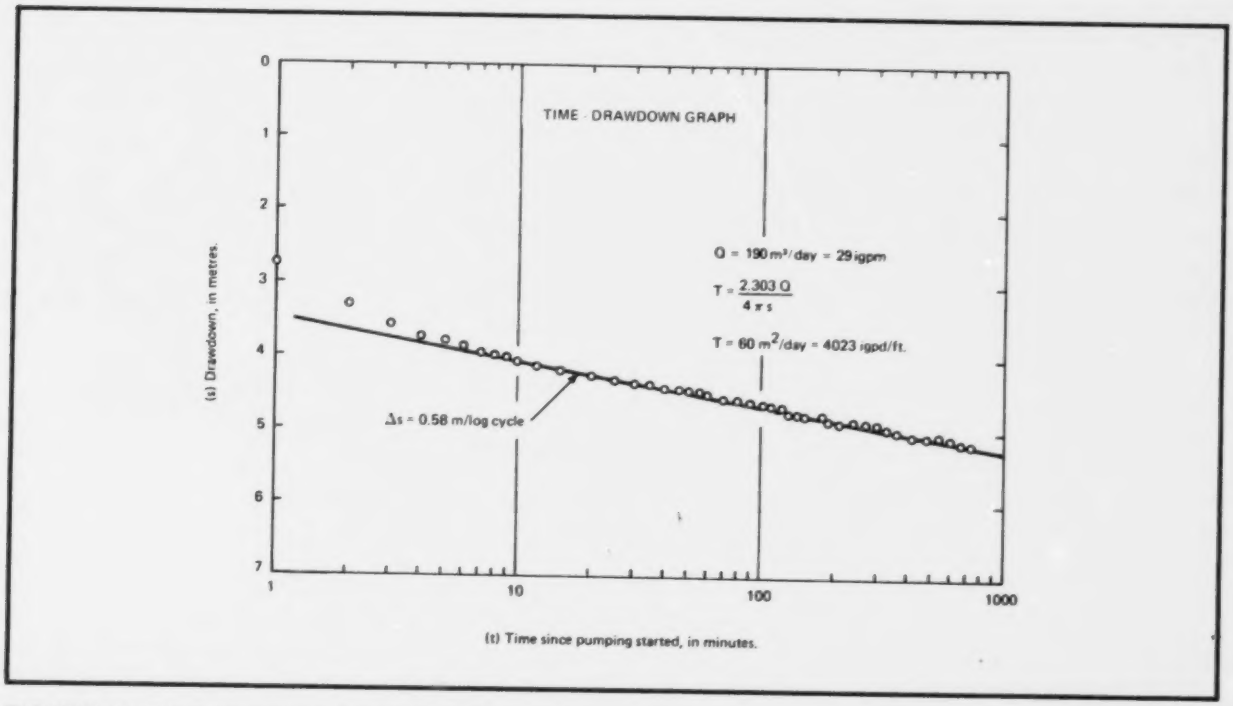



**FIGURE 48.** Time-drawdown graph, PL79-1.

culation in highly permeable sandstone beds. The shallow sandstone unit shown in figure 51 was of such high hydraulic conductivity that 18 cm (7 in) surface casing had to be installed before drilling could proceed. The results of a 24-hour aquifer test of the lower thick sandstone unit are given in figure 52. Analysis of the drawdown data indicate a transmissivity of 62 m²/day (4174 igpd/ft²). Since the thickness of this sandstone unit is estimated to be about 30 m (100 ft), the hydraulic conductivity is probably about 2.0 m/day (42 igpd/ft²). This aquifer represents a significant source of groundwater previously unrecognized in the Pine Lake research basin. Safe yield calculations give the figure $Q_{20}$ = 2620 m³/day (400 igpm). TDS was determined from groundwater samples to be around 600 mg/L with a facies type of Na-$HCO_3$.

**Testhole PL79 - 4: (15-8-37-25-W4)**

This testhole was drilled with a rotary rig to a depth of 152.4 m (500 ft) and was the most remote of the four exploration sites. The purpose of the hole was to obtain geologic data in an unexplored area and to attempt a completion in a thick, deep sandstone unit (fig. 23). The exploration results of this testhole are given in figure 53. The depth to static water level exceeded 60 m (200 ft) and casing had to be installed to about 90 m (300 ft) so that proper aquifer testing could be accomplished. The results of a 12-hour aquifer test (fig. 54) indicated that the hydraulic conductivity of the deep sandstone sequence is low. This was qualitatively expected from the fine-grained, bentonitic nature of the drill cuttings and later confirmed by the low transmissivity value of 4.5 m²/day (300 igpd/ft²). Studies conducted by Gabert (1975) on the same stratigraphic unit concluded with similar results. Na-$HCO_3$ type groundwater is still prevalent at this depth and TDS is around 1175 mg/L.

## ESTIMATES OF REGIONAL GROUNDWATER RECHARGE

Traditional methods for estimating regional groundwater recharge in western Canada are:

1. Field instrumentation at both the recharge and discharge areas of the flow system.
2. Analysis of baseflow components from streamflow hydrographs.

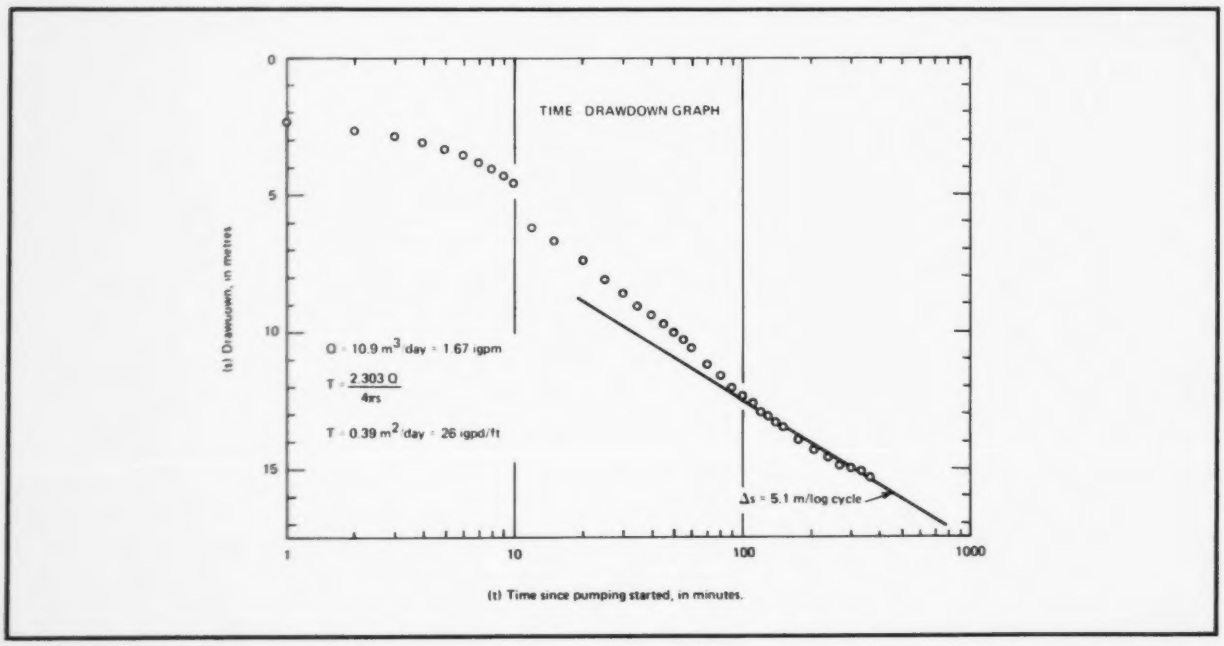



**FIGURE 50.** Time-drawdown graph, PL79-2.

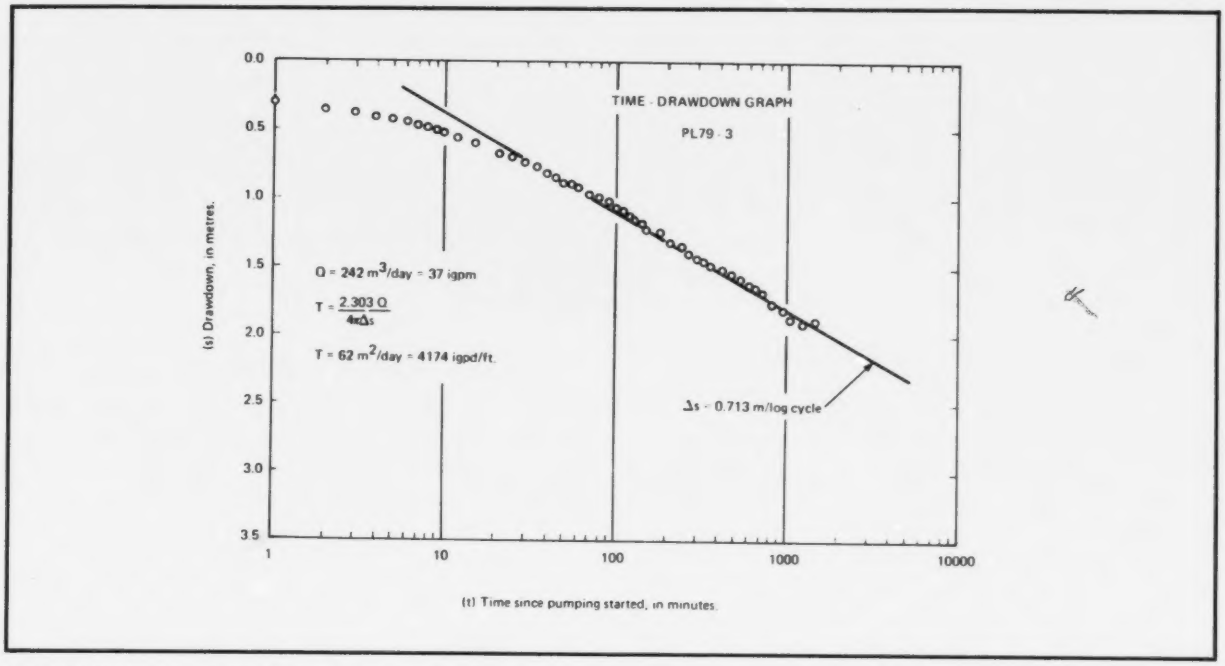



**FIGURE 52.** Time-drawdown graph, PL79-3.

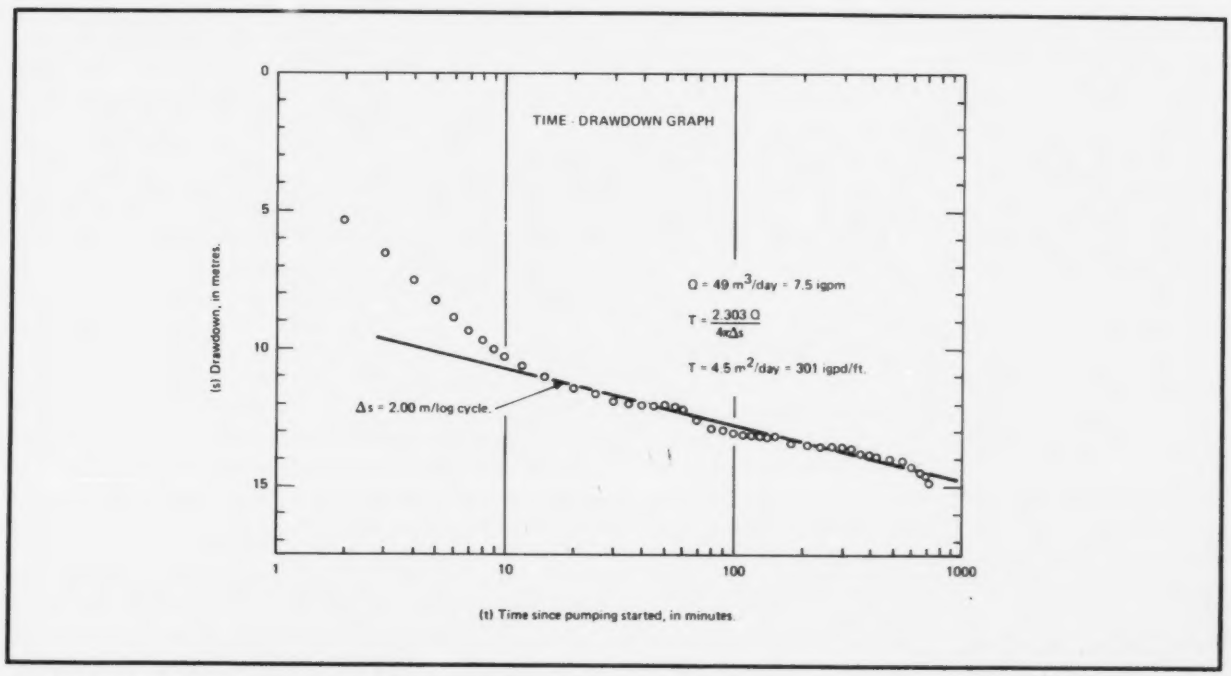



**FIGURE 54.** Time-drawdown graph, PL79-4.

3. Application of soil moisture budgets based on precipitation and evapotranspiration data.
4. Flow net analysis of actual field derived piezometric data.
5. The use of steady-state drainage equations.
6. Calculation of regional groundwater flow through flow net analysis of numerical models.
7. Complete water budgets of instrumented drainage basins.

The application of a few of these techniques are discussed below.

## ANALYSIS OF ANNUAL WATER-TABLE FLUCTUATIONS

Tóth (1962) noted that there should be a quantitative relationship between the saturated flow of groundwater and fluctuation of the water table. Groundwater flow from recharge areas on the elevated ridges to discharge areas in the valley bottom should produce a corresponding drop and rise in the water table. At places midway between the divide and drainage way, groundwater flow is essentially lateral so the water table should remain nearly constant. In a steady-state groundwater system, the rise in water levels in discharge areas should theoretically equal the fall of levels in recharge areas for homogeneous and isotropic media. Fluctuations of water-table elevations are also, however, caused by natural and induced hydrologic phenomena, the most important of which include precipitation events, evapotranspiration, and pumping of groundwater from wells.

The most convenient time to measure the effect of groundwater flow on water-table fluctuations in western Canada is during the winter months. In the Pine Lake area, the ground is usually frozen to a depth of a few metres, depending on the amount of snow cover, and remains so throughout the months of November to March. Freezing of the ground reduces the effects of infiltration and evapotranspiration on the water table to nil and, if observation wells are not influenced by the pumping of wells, quantitative analysis of water-table hydrographs should be possible. A limiting factor of this type of analysis is the effect of the freezing process which causes moisture transfers in the unsaturated zone and thus a natural lowering of the water table. Freeze and Banner (1970) studied the relationship of soil moisture, frost, and infiltration at an instrumented experimental plot in southern Alberta. They found that the effect of freezing on lowering water tables was insignificant.

Using the notation of Tóth (1968), the natural yield of a flow system (i) for the time interval (t) is given by the equation:

$$Q_{i,t} = Sy \cdot f_{d,t} \cdot A_{i,d} = Sy \cdot f_{u,t} \cdot A_{i,u} \qquad (10)$$

where Sy = average specific yield of the rocks, $f_{d,t}$ = average drop of water levels in the area of downward flow ($A_{i,d}$), and $f_{u,t}$ = average rise of the water table in the area of upward flow ($A_{i,u}$) provided the water table fluctuations are only the result of groundwater flow from recharge to discharge areas. Equation (10) may also be expressed in terms of depth over the respective areas:

$$q_{i,t,d} = \frac{Q_{i,t}}{A_{i,u}} = Sy \cdot f_{d,t} \qquad (11)$$

and

$$q_{i,t,u} = \frac{Q_{i,t}}{A_{i,u}} = Sy \cdot f_{u,t} \qquad (12)$$

Tóth (1968) also showed that, in cases where the seasonal changes of the hydraulic gradients in the flow system are small in comparison to the average gradient, the total yield of the system ($Q_{i,T}$) over a complete annual cycle is given by:

$$Q_{i,T} = Q_{i,t} \cdot \frac{T}{t} \qquad (13)$$

This equation represents the natural basin yield if a single flow system exists in a basin; otherwise, the total natural yield would consist of a summation of the $Q_{i,T}$ for all flow systems in the basin.

Long-term water-table hydrographs are available for three shallow observation wells in the Pine Lake research basin and are here denoted as Elnora no. 2, Elnora no. 3, and Elnora no. 4. These wells are spaced almost equidistantly over the

drainage divide in the southwestern corner of the basin; Figure 3 shows their exact locations. Elnora no. 2 is 5.2 m (17 ft) deep and is completed in a surficial sand deposit, presumably outwash. Elnora no. 3 is on top of the divide where it was drilled to a depth of 18.9 m (62 ft) and completed in an interbedded sequence of shale, siltstone, and sandstone. The till at this location was found to be 4.9 m (16 ft) deep. Elnora no. 4 is 13.7 m (45 ft) deep and is completed in a clayey till overlain by outwash sand. Lithologic details of this well are also given in figure 29. Alberta Research Council staff constructed these wells and automatic water-level recorders have produced hydrographs since 1962.

Presenting the complete hydrograph records for all three observation wells would be unwieldy. To illustrate the typical annual response of the water table in a recharge area, figure 55 shows the 1967 hydrograph of Elnora no. 3. One feature of all three hydrographs is the gradual rise in water levels beginning in late April and leveling off near the end of July. This feature is primarily a function of spring thaw and annual precipitation patterns and is well exhibited by the example of figure 55 (compare with figure 10). Fluctuations in the hydrograph in figure 55 for the period after May likely represent the effects of rainfall and evapotranspiration, although this pattern continues into December. The decrease of evapotranspiration throughout the early fall sustains the water-table level achieved by high precipitation in August, but eventually precipitation decreases (figs. 8 and 9) and levels drop slowly until the ground is completely frozen in early November. Because all three observation wells are in recharge areas, a drop in the water-table during the winter months (November to March) is expected due to the natural gradient of groundwater flow and the absence of recharge by precipitation. This was the case in all three observation well records and the nature of the decline shown on figure 55 is typical.

In order to quantify the effect of the groundwater

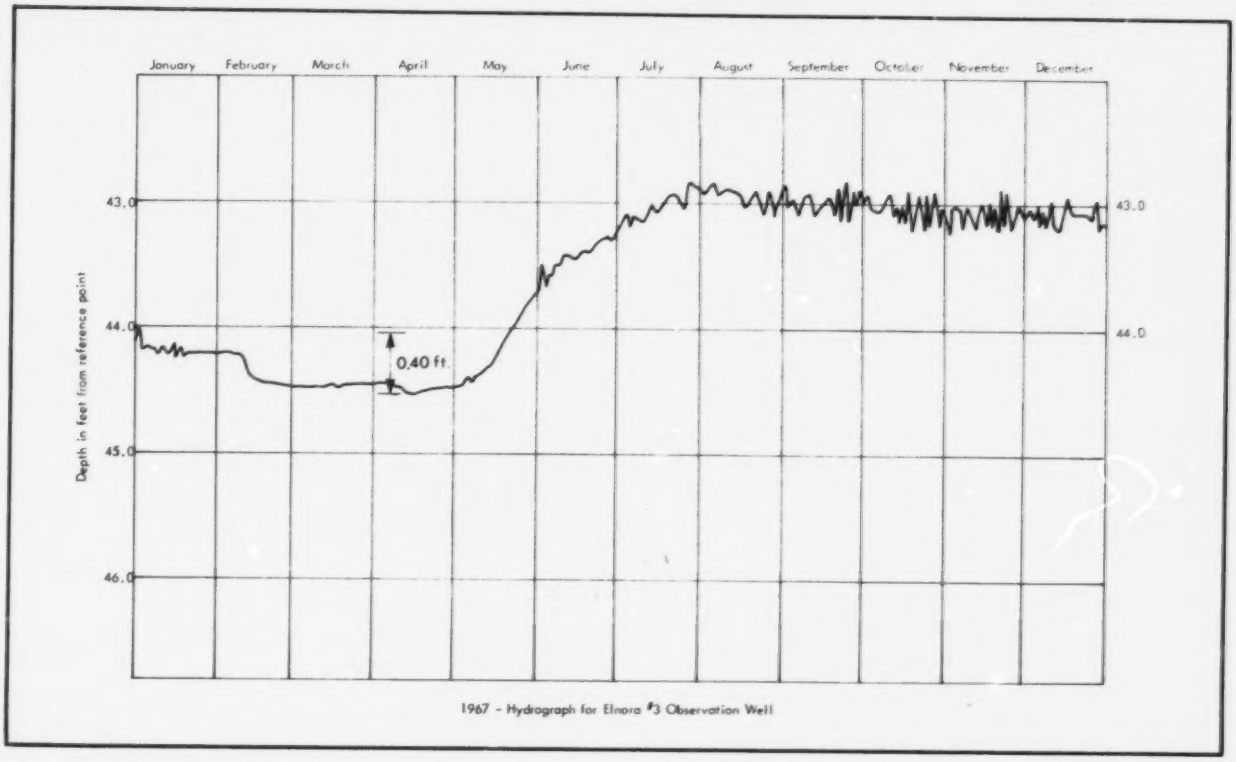



**FIGURE 55.** Hydrograph of an observation well in the southwestern part of the basin.

flow system on the water-table fluctuations observed in the Pine Lake area, the technique used by Tóth (1968) was applied to the hydrographs of Elnora no. 2, no. 3, and no. 4. Average changes in the water-table elevations from November to March were graphed, as shown partially in figure 55. Table 7 summarizes the results of this analysis for a 15-year record (1962-1976) and the mean water-level change calculated for a 15-year record (1962-1976) and the mean water-level change calculated for each observation well. In all of the calculations, sporadic pumping in nearby domestic wells (fig. 3) is assumed not to have affected the water table appreciably.

TABLE 7.

Summary of hydrograph analyses, groundwater observation wells. Values represent water level changes during the period November to March

(+ = rise in level, - = drop in level)

| Year | Elnora #2 (feet) | Elnora #3 (feet) | Elnora #4 (feet) |
|---|---|---|---|
| 1962 | -0.38 | +0.24 | +0.02 |
| 1963 | -1.56 | -0.19 | -0.11 |
| 1964 | -0.66 | 0.00 | -0.07 |
| 1965 | -2.10 | -0.32 | -0.28 |
| 1966 | -1.76 | -0.40 | -0.26 |
| 1967 | -0.60 | -0.44 | -0.19 |
| 1968 | -1.40 | -0.52 | 0.00 |
| 1969 | -1.64 | -0.74 | -0.15 |
| 1970 | -1.48 | -0.36 | -0.26 |
| 1971 | -1.34 | -0.52 | -0.26 |
| 1972 | -1.58 | -0.56 | -0.07 |
| 1973 | - | - | -0.14 |
| 1974 | -2.10 | - | -0.23 |
| 1975 | -1.40 | - | -0.20 |
| 1976 | -0.75 | -0.40 | -0.11 |
| Mean | -1.34 | -0.405 | -0.155 |

Based on the data given in table 7, the following calculations of average depth of groundwater exchange ($Q_T$) can be made with equations (11), (12) and (13), along with estimates of specific yield for the local geologic deposits:

Elnora no. 2;
$Q_T = (0.20)(1.34 \text{ ft}) \cdot (12)/(5) = 19.6 \text{ cm } (7.7 \text{ in})/\text{year}$

Elnora no. 3;
$Q_T = (0.10)(0.405 \text{ ft}) \cdot (12)/(5) = 3.0 \text{ cm } (1.2 \text{ in})/\text{year}$

Elnora no. 4;
$Q_T = (0.20)(0.155 \text{ ft}) \cdot (12)/(5) = 2.3 \text{ cm } (0.89 \text{ in})/\text{year}$

Assuming an average annual precipitation of about 46 cm (18 in) for this part of the basin, the magnitude of groundwater exchange (recharge) represent approximately 43 percent, 7 percent, and 5 percent of annual precipitation for Elnora no. 2, no. 3, and no. 4, respectively. Tóth (1968) arrived at a value of 9 percent of annual precipitation for recharge using the same method in the Threehills drainage basin (fig. 2). Values of 5 percent and 7 percent are probably more representative of average recharge rates in the research basin than the 43 percent estimated for the surficial sand. Freeze (1969b) conducted a detailed hydrologic budget of a drainage basin in Saskatchewan and found that a large proportion of total groundwater recharge was found in a central outwash deposit. Rates of recharge in the Saskatchewan basin were calculated to dominate between 6 percent and 30 percent of annual precipitation. Since climatic conditions and surficial geology are similar to that encountered in the Pine Lake basin, the values of groundwater exchange calculated from the hydrograph analyses may indeed prove to be good preliminary estimates of areal recharge in the Pine Lake research basin.

**Application of a Steady-State Drainage Equation**

Meyboom (1966a) was the first to explore the possibility of using steady-state equations (originally developed for drainage of stratified soils) to calculate regional groundwater discharge in western Canada. He based his analogy on the fact that groundwater flow in a layered medium may be schematized by nearly vertical flow through an upper less permeable layer, horizontal flow through a lower permeable horizon (so-called Dupuit flow), and essentially radial flow in the vicinity of an open drainage way. Meyboom (1967a) applied the steady-state equation of Ernst (1963) to calculate groundwater discharge in the Arm River drainage basin in Saskatchewan and arrived at a numerical value consistent with that derived from the summation of baseflow and evapotranspiration estimates.

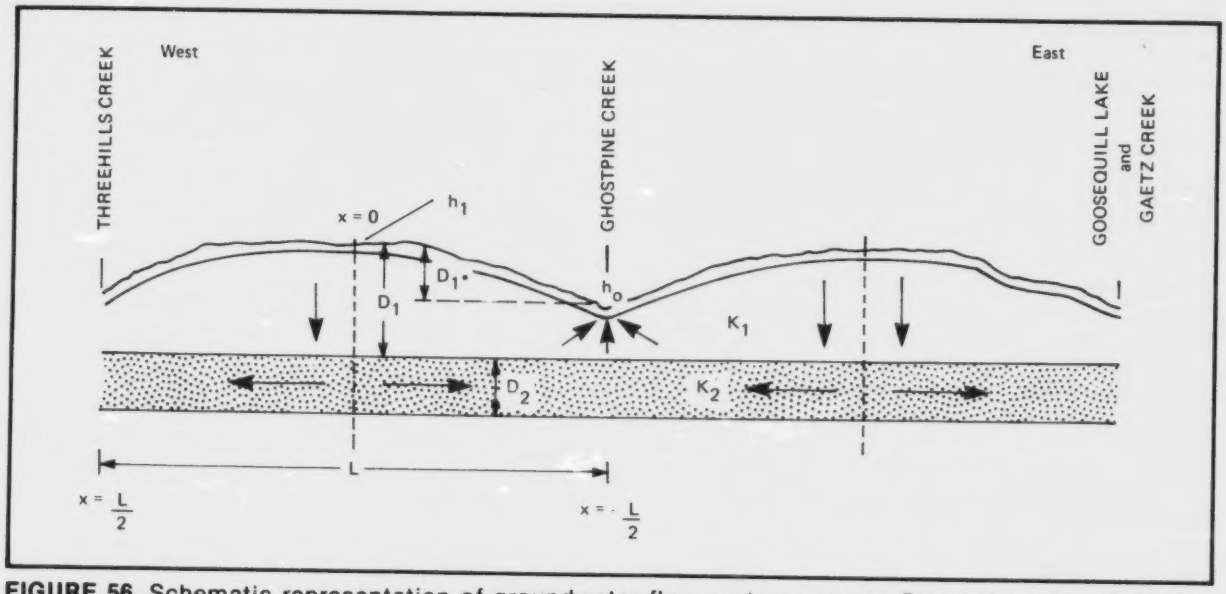



**FIGURE 56.** Schematic representation of groundwater flow systems across Pine Lake research basin, near the north end of the lake (h = hydraulic head, K = hydraulic conductivity, D = thickness of strata, L = distance between parallel drainage channels).

The similarity of Meyboom's (1967a, fig. 3) schematic representation of groundwater flow in the Arm River basin to that inferred for the Pine Lake research basin (fig. 39) encouraged the writer to try Meyboom's method of analysis.

A schematic representation of groundwater flow across the Pine Lake research basin is given in figure 56. This diagram, based on the conceptual model presented in figure 39, may not hold for all parts of the Pine Lake basin. Nevertheless, the hydrogeologic model of a symmetric drainage basin consisting of a permeable layer overlain by a thicker, less permeable unit will serve as a first approximation to the actual complex stratigraphy. The steady-state drainage equation for this particular hydrogeologic configuration derived by Ernst (1963) and used by Meyboom (1967a) is:

$$h_1 - h_o = Nc_1 + \frac{NL^2}{8(K_1D_1 + K_2D_2)} + NLw \qquad (14)$$

where the coefficients are defined and evaluated for the Pine Lake basin as follows (fig. 56):

L = distance between parallel drainage basins = 13 km

$h_1$ = total hydraulic head of the water table at the drainage divide = 945 m

$h_o$ = water level in the drainage channel=890 m

$D_1$ = thickness of the low permeability layer = 90 m

$D_2$ = thickness of the deep permeable unit = 55 m

$K_1$ = hydraulic conductivity of the low permeability layer = 0.1 m/day

$K_2$ = hydraulic conductivity of the permeable sandstone unit = 2.0 m/day

$D_1^*$ = thickness of the low permeability layer midway between drainage channels and to a depth equal to the bottom of the channel (fig. 56) = 60 m

$c_1 = D_1^*/K_1$ = vertical resistance = 667 days

$D_1^{**}$ = thickness of the low permeability layer at the drainage way = 55 m

$R_0$ = radius of the wetted perimeter of the drainage channel = 5 m

$w = 1/\pi K_1 \cdot \ln(4D_1^{**}/Ro)$ = vertical resistance = 11 days/m

N = total groundwater discharge confined to the drainage way. Similar drainage equations are also presented by Bear (1979).

Solving Equation (14) for the value of groundwater discharge results in N = 5 cm/yr (2 in/year) or approximately 11 percent of the annual precipitation. The steady-state drainage equation of Ernst (1963) requires the following assumptions: (1) the

strata are of constant thickness, (2) each layer is homogeneous and isotropic, (3) $(D_1 + D_2)/L$ less than 0.25, (4) $K_1D_1$ less than 0.1 $K_2$ $D_2$, (5) the water table is nearly horizontal, (6) drainage takes place by parallel streams only, and (7) groundwater discharge is restricted entirely to the drainage channel. Although several assumptions are met or closely approximated in the Pine Lake basin, whether or not it is realistic to assume restriction of groundwater discharge to the drainage channel in light of the field mapping (fig. 38) is questionable.

### Interpretation of Streamflow Records

The method of baseflow separation as a means for estimating regional groundwater discharge has received considerable attention in western Canada (Meyboom, 1961; Farvolden, 1963b; Tóth, 1968; Freeze, 1969a). Based on two years of records, crude estimates of annual groundwater runoff over the drainage area amount to 0.4 cm (0.17 in) and 0.3 cm (0.11 in) for the years 1967 and 1969. According to these figures, groundwater discharge to the drainage ways amounts to only about 1 percent of annual precipitation.

### Natural Basin Yield

Freeze and Witherspoon (1968) defined the natural basin yield as the natural quantity of groundwater flow through an undeveloped drainage basin. It is easily calculated from quantitative flow nets and provides an estimate of the amount of groundwater that can be safely withdrawn from a basin. Freeze (1971) showed, however, that a much more detailed assessment is required to obtain quantitative values of optimum or safe yield.

As a first approximation, we can make use of figure 40 to calculate natural yield in the Pine Lake research basin. This particular simulation gave rise to two major flow systems. The regional system consists of nearly vertical flow across the low permeability units to sub-horizontal flow through the sandstone aquifers. Superimposed near the regional discharge area is a very strong local flow system. Using the hydraulic conductivities specified and Darcy's law, the natural discharge through the regional system is 15 $m^3$/day (per metre of thickness perpendicular to the section). A similar calculation for the local flow system gives a value of 40 $m^3$/day/m (2800 igpd/ft). Total groundwater discharge through this part of the basin is, therefore, approximately 55 $m^3$/day/m (4000 igpd/ft). Obviously, the area near Pine Lake would seem to be the optimal location for any major groundwater development project.

Actual rates of recharge across the basin cannot be immediately determined from figure 40 without accurate hydraulic conductivity measurements of the glacial drift. At present, only an estimate can be made through the published values of permeability (till) given earlier. If we assume a vertical hydraulic conductivity of $5 \times 10^{-5}$ m/day ($10^{-3}$ igpd/ft²) and use a hydraulic gradient of 0.7 (from figure 40), then an estimated recharge rate is 1.3 cm/yr (0.5 in/yr). This value would be considerably higher for the outwash deposits around Pine Lake.

## WATER BALANCE CONSIDERATIONS

In its simplest form, the hydrologic budget equation or water balance is:

$$I - O = dS/dt \qquad (15)$$

which states that the inflow into a hydrologic system during a given period minus the outflow during a given period must equal the change in storage within the system. An extension of this simple water budget equation to the Pine Lake research basin would have to be considerably more detailed in order to quantify all the hydrologic components. Such an equation could be written for an annual period as:

$$P + R_i - R_o + G_i - G_o - ET - Q_p = S_s + S_g \qquad (16)$$

where P = precipitation, $R_i$ = surface runoff into the basin, $R_o$ = surface runoff out of the basin, $G_i$ = groundwater flow into the basin, $G_o$ = groundwater flow out of the basin, ET = evapotranspiration, $Q_p$ = total groundwater pumpage for domestic and livestock purposes, $S_s$ = change in storage of surface-water reservoirs, and $S_g$ = change in storage of groundwater system (saturated and unsaturated zone).

If it can be assumed that the groundwater divide coincides with the surface divide (fig. 41), $R_i = 0$ and if groundwater pumpage is negligible, $Q_p = 0$. Equation (16) can be further simplified by considering a long period of time (several years) such that $G_i = G_o$ (throughflow) and $S_s = S_g = 0$, hence;

$$P - R_o - ET = 0 \qquad (17)$$

where P is now the average annual precipitation, $R_O$ = average annual surface runoff, and ET = average annual evapotranspiration. Given the values of precipitation and streamflow runoff, average annual evapotranspiration could be estimated using equation (17), a parameter that is often difficult to measure in the field. Assuming that the average annual precipitation for the Pine Lake research basin (table 1) is approximately 46 cm and that the average annual runoff is 2 cm over the basin, mean annual evapotranspiration over the research basin can be crudely estimated by equation (17):

$ET = P - R_O = 44$ cm (17.2 in)

This value can be compared with the potential evapotranspiration of 51 to 53 cm (20 to 21 in) calculated in table 1 and that of actual evapotranspiration estimated as 41 to 46 cm (16 to 18 in) by the Government and University of Alberta (1969).

Without more quantitative hydrologic data, a detailed analysis of the water budget in the Pine Lake basin would be unfounded. Freeze and Cherry (1979) concluded that applying steady-state water-budget equations is in reality inadequate for accurate evaluations of the hydrologic regime of a drainage basin. They base this statement on the fact that the approach does not take into account the areal and temporal variations in precipitation, evapotranspiration, runoff, recharge, or discharge. Nevertheless, studies have shown (Freeze 1969a, 1969b) that with a minimum amount of instrumentation and logical assumptions, a significant understanding of both the groundwater and surface water regime can be achieved through the application of simple, lumped-parameter water budget equations.

## CONCLUSIONS AND RECOMMENDATIONS

As outlined at the beginning of the text, the main purpose of this evaluation was to provide a preliminary framework for instrumentation and future hydrologic studies. Before examining these research possibilities, a summary of the major findings is presented.

## SUMMARY AND CONCLUSION

### Geographical Aspects

(1) The Pine Lake research basin comprises a 230 km² (90 sq mi) portion of the much larger Ghostpine Creek drainage basin. Topography is rolling to hilly and maximum relief is approximately 180 m (600 ft). The present topography is essentially a subdued replica of a buried bedrock topography.

(2) Drainage is moderately developed in the basin, except in extensive areas of knob-and-kettle terrain where no integrated surface drainage exists. Pine Lake and Ghostpine Creek are the major hydrographic features in the basin. Ghostpine Creek is an intermittent stream where streamflow is highly regulated by surface runoff. Pine Lake is a permanent body of water that receives a significant amount of local groundwater discharge.

(3) The research basin is dominated by the Black Soil Group which reflects the surficial geology. These soils support a healthy phreatophytic vegetation and, therefore, transpiration loss of soil moisture is a major component of the local hydrologic cycle.

(4) Mean annual precipitation is approximately 46 cm (18 in) and potential evapotranspiration was calculated by the Thornthwaite method to be about 51 cm (20 in) annually. A crude water-budget calculation yielded an actual evapotranspiration of 44 cm (17 in) as an annual mean over the basin.

(5) Physiography has a substantial influence on groundwater in the Pine Lake area. Most important is its control on the rates and distribution of recharge and the pattern of groundwater flow. Unfortunately, field data is currently not available to quantify this observation.

### Geology

(1) The entire basin is underlain by bedrock strata of the Paskapoo Formation. It is characterized by a complex succession of sandstone, siltstone, shale, and minor coals which exhibit a very gentle structural dip to the west. The Paskapoo Formation ranges from about 110 m (350 ft) thick in the south to over 360 m (1200 ft) in the northeastern part of the research basin.

(2) The Lower Ardley 'B' coal zone is the most persistent marker bed in the Paskapoo Formation. The sequence of strata above the coal zone contains two regionally extensive units dominated by

sandstone beds: a deep basal unit that averages about 60 m (200 ft) thick and a near-surface unit that is usually less than a 30 m (100 ft) thick. The shallow sandstone unit is the major aquifer in the Pine Lake basin.

(3) The glacial drift is generally less than 15 m (50 ft) thick, but can exceed 43 m (140 ft) in areas of hummocky moraine and along a buried bedrock drainage way currently occupied by Pine Lake and Ghostpine Creek. Till is the most abundant drift material. Deposits of sands and gravel are found in outwash deposits near Pine Lake, along Ghostpine Creek, and in a few esker ridges.

**Hydrologic Results**

(1) Based on two years of streamflow data, annual surface runoff may be in the magnitude of 2 cm (0.08 in) over the drainage basin. Estimating the baseflow component from such scanty runoff data is highly questionable, although an "average" value of 0.36 cm (0.14 in) was calculated using minimum monthly discharges.

(2) Pine Lake is a major groundwater discharge feature. It is difficult to perform a meaningful water budget of this system, without quantitative data of evaporation rates, surface water inflows and outflows. Analysis of Lake level hydrographs (4 years) yielded a mean annual net evaporation equal to 48 cm (19 in).

(3) The water table is a subdued replica of the topography. Regional groundwater flow is from broad recharge areas on the surrounding uplands and hummocky terrain towards wide discharge areas centered along the drainage ways. This is supported by the fact that hydraulic heads are observed to decrease with depth on the drainage ridges and increase with depth along the valley bottom. In addition, flowing wells and numerous springs are concentrated in the vicinity of major topographic lows.

(4) Pump-test data and geological considerations indicate the following ranges of hydraulic conductivity: sandstone, 0.5 to 25 m/day (10 to 500 igpd/ft$^2$); siltstone, 0.25 to 0.50 m/day (5 to 10 igpd/ft$^2$); shales, 0.05 to 0.25 m/day (1 to 5 igpd/ft$^2$); sand and gravel 5 to 100 m/day (100 to 2000 igpd/ft$^2$); and till, $10^{-5}$ to $10^{-2}$ m/day ($10^{-3}$ to 1 igpd/ft$^2$). Anisotropy ratios are estimated to be about 50 to 100:1 for the bedrock, 10:1 for the till, and 1:1 for surficial sands and gravels. Field-determined storage coefficients are rare, but most bedrock aquifer tests can be expected to obtain storativities in the $10^{-4}$ to $10^{-3}$ range, depending on the degree of local confinement.

(5) Four major hydrostratigraphic units are delineated: unit 1 is assigned to the glacial drift; unit 2 includes those strata presently penetrated by domestic wells, down to the top of the thick basal sandstone; unit 3 is assigned to the strata of the thick basal sandstone, down to the Lower Ardley 'B' coal zone; and unit 4 to the rocks below the coal zone. Such a division is partly conjectural, but it provides a base upon which future studies can build.

(6) Groundwater flow in the research basin is most appropriately treated as a regionally unconfined system in a heterogeneous and anisotropic rock media. The absence of regional confining units and the hydraulically connected nature of the subsurface strata support this interpretation. As a first approximation, the groundwater regime can also be considered to be in steady state. This is supported by the fact that the configuration of the water table has not changed appreciably over the years, fluctuations of water-table levels are small compared to the saturated thickness of the system, and pumping of groundwater in the basin is insignificant. A numerical model, based on these assumptions, gave a simulated flow pattern which qualitatively agrees with the conceptual-field model of flow in the Pine Lake basin.

**Hydrogeochemistry**

(1) The complex mineralogical assemblages in the glacial drift and operation of geochemical processes during infiltration are largely responsible for determining the existing hydrochemical facies pattern. Sodium-bicarbonate is by far the most prominent hydrochemical facies in the bedrock, but superimposed upon it are facies of Ca-Mg-$HCO_3$, Na-$SO_4$-$HCO_3$, and Ca-Mg-$SO_4$-$HCO_3$. Total dissolved solids are usually less than 1000 mg/L in the groundwater, at least within 90 m (300 ft) of the surface.

(2) Drift groundwaters are usually hard and characterized by the Ca-Mg-$HCO_3$ facies or Ca-Mg-$SO_4$-$HCO_3$ facies where soluble sulfate minerals are present. Geochemical processes such as cation exchange and sulfate reduction are responsible for the transition of these shallow "recharge" facies to the dominant Na-$HCO_3$ water at depth.

(3) In general, correlation of hydrochemical facies with groundwater flow patterns is currently untenable and should receive considerably more research before major conclusions are drawn.

### Groundwater Resources

(1) Nearly all wells in the Pine Lake basin are completed in bedrock aquifers, mainly because of ease in well construction, better water quality, and higher probability of penetrating a dependable supply of water. In most parts of the basin, shallow bedrock wells should be able to obtain sustained 20-year safe yields in the 0.4 to 1.9 L/s (6 to 25 igpm) range. Wells completed in the thick shallow sandstone unit may be capable of exceeding 7.5 L/s (100 igpm) in parts of the research basin.

(2) A major conclusion to be drawn from the exploration program is that significant groundwater resources exist in the deep, thick sandstone units, but hydraulic conductivity is highly regulated by lithological facies. Furthermore, the program demonstrated that deep groundwater flow systems exist in the research basin, as predicted by theoretical considerations.

(3) Through the analysis of water-table fluctuations in three observation wells in a recharge area, the average depths of recharge amounted to 20 cm (7.7 in), 3 cm (1.2 in), and 2 cm (0.9 in), annually. Application of a steady-state drainage equation to a schematic representation of the Pine Lake basin resulted in an estimate of annual discharge of 5 cm (2 in) over the basin. Quantitative evaluation of the distribution of groundwater recharge will require a more sophisticated approach than those above if meaningful groundwater budgets are to be performed. A preliminary numerical model indicates that natural basin yield is about 55 $m^3$/day/m (4000 igpd/ft). Nearly three times as much flow occurs in the local flow system around Pine Lake as passes through the regional groundwater flow system.

## RECOMMENDATIONS

### Instrumentation

In terms of evaluating the quantitative aspects of the groundwater regime, some form of piezometer grid must be established in the Pine Lake basin. Based on the preliminary assessment of the hydrogeology and groundwater flow pattern, the most functional design would consist of several piezometer nests arranged in a line and kept approximately parallel to the maximum topographic gradient. Ideally, it would be very useful to have three of these line networks, one across each of the northern, central, and southern parts of the research basin. Because of the near symmetry of the basin, individual lines would only need to extend from one drainage divide to the valley bottom, but at least one should extend across the complete basin to investigate the symmetry hypothesis.

Although the number of nests along each piezometer line could be varied with the local conditions, a minimum of three would be required: one near the ridge, one midway on the basin's flank, and one at the drainage way. This initial instrumentation phase could later be expanded by installing piezometer nests between existing ones and so on.

Individual piezometer nests would have to be designed for the local site conditions. On the ridges this could entail locating the deepest piezometer at a depth of 150 m (500 ft) or more. Towards the drainage bottoms, maximum piezometer depth would not need to exceed 120 m (400 ft) in order to penetrate the main hydrostratigraphic units. Each nest should consist of at least three piezometer openings completed at some arbitrary depth interval, either in separate small-diameter boreholes side by side or possibly in the same hole.

Commercial piezometer units offer a number of sophisticated designs. These units use a variety of pressure transducers, packer assemblies, and advanced electronics to take measurements of head or hydraulic conductivity and to obtain

samples for chemical analysis at several piezometer openings. In addition to a sufficient number of piezometers at a site, a water-table well should also be installed and equipped with a recorder. Good estimates of hydraulic conductivity can be obtained from the piezometers by applying the Hvorslev (1951) method on recovery data.

Instrumentation of the unsaturated zone should also be considered. Experimental plots could be established at both a recharge and discharge area and the relationship between infiltration, evapotranspiration, soil moisture, and groundwater recharge or discharge investigated. This type of site could include a precipitation gauge, neutron probe access tubes, water-table observation well, tensiometers, and perhaps a shallow piezometer nest.

A complete instrumentation plan for the subsurface should not ignore surface water completely. Only one meteorological station currently exists in the basin, and that is in the northern reaches. Temporary precipitation gauges should be established, preferably to the west of Pine Lake and in the southern part of the basin. Runoff is one of the easiest components of the hydrologic cycle to measure in the field and such data would be desirable for the Pine Lake research basin. Establishing a permanent streamflow gauging station at the southern outlet of the research basin is a prerequisite. Temporary stations would have to be installed at the major inlets and outlets of Pine Lake if a serious analysis of its water budget is attempted in the future. The actual interaction between Pine Lake and the groundwater regime would best be defined through piezometric analyses and installation of seepage meters.

**Future Study**

It is apparent from this investigation that significant amounts of information can be derived from careful interpretation of basic data. The exploration program was successful at confirming the accuracy of this data. Future drilling programs should concentrate on obtaining hydraulic conductivities of the deep sandstone aquifers and properties of the unsaturated zone. Now that the hydrogeology has been studied, research emphasis should be shifted from data collection to experimentation with new field techniques or technology.

Perhaps the most important recommendation that can be made is more application of numerical modelling techniques. As the general aspects of the hydrogeologic environment and groundwater regime have been determined, numerical modelling of the basin could provide additional insight. Detailed flow net studies could be used to identify the spatial distribution of recharge and discharge and quantitatively investigate their orders of magnitude for various boundary conditions. Numerical modelling could also be integrated with future field programs to help the researcher decide on optimal locations of piezometers or other instrumentation. The role of modelling in understanding the interaction between Pine Lake and the groundwater flow systems could be invaluable. Time-series analysis of both groundwater and lake-level hydrographs may also provide interesting answers to the interaction problem. The idea here is not necessarily to provide numbers but rather insight into the hydrology of the basin.

Hydrogeochemistry is poorly understood in the basin and deserves future research considerations in two major areas. First, geochemical evaluation of groundwaters could be investigated using the techniques put forth by Schwartz and Domenico (1973) or Plummer and Back (1980). Sophisticated computer programs are currently available that make studies of this type tenable. Second, an effort should be made to obtain dispersivity data and establish monitoring sites. Not only would this be of local benefit for environmental reasons, but as there are few field-research sites in western Canada, the Pine Lake basin would make an ideal candidate.

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## APPENDIX A: Shallow Well and Spring Data

Notes to Appendix A

1. Column 3: Elevation of land surface in the vicinity of the well as determined by extrapolation from topographic map with 25 ft contour interval.
2. Column 9: Type of well refers to the geology of the material in which the well is completed.
3. Column 11: Available drawdown (H) is defined as the difference between static water level and the top of an aquifer.
4. Column 12: T = transmissivity, K = hydraulic conductivity as determined from bail test.
5. Column 13: $Q_{20}$ = maximum discharge rate which can be sustained over a 20-year period without drawdown below the top of an aquifer (calculated by $Q_{20} = (T)(H)/2110$).

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| 1 | 5-1-35-24W4 | 2825 | 70 | | Shothole | Flowing 2825 + |
| 2 | 9-2-35-24W4 | 2825 | 75 | | Domestic | Flowing 2825 + |
| 3 | 3-4-35-24W4 | 2980 | 140 | 100 - 140 | Domestic stock | 90.2 2890 |
| 4 | 8-4-35-24W4 | 2970 | 108 | | Domestic stock | 35 2935 |
| 5 | 10-7-35-24W4 | 3110 | 190 | | Domestic | |
| 6 | 14-7-35-24W4 | 3085 | 122 | 70 - 122 | Domestic stock | 69 3016 |
| 7 | 14-9-35-24W4 | 3050 | 150 | | Domestic | 131 2919 |
| 8 | 5-9-35-24W4 | 3030 | 230 | 221 - 230 | Domestic | 130 2900 |
| 9 | 16-9-35-24W4 | 3045 | 252 | | Domestic stock | 180 2865 |
| 10 | 16-9-35-24W4 | 3045 | 262 | 240 - 262 | Domestic stock | 170 2875 |
| 11 | 10-9-35-24W4 | 3060 | 190 | 140 - 190 | Stock | 123 2937 |
| 12 | 7-10-35-24W4 | 2910 | 300 | | | 30 2880 |
| 13 | 15-12-35-24W4 | 3055 | 230 | | Domestic | 60 2995 |
| 14 | 1-13-35-24W4 | 3035 | 215 | | Domestic | |
| 15 | 9-13-35-24W4 | 3035 | 210 | | | 170 2865 |
| 16 | 16-14-35-24W4 | 3075 | 266 | 200 - 266 | Domestic | 221 2854 |
| 17 | 1-15-35-24W4 | 2875 | 85 | | | 15 2860 |
| 18 | 8-15-35-24W4 | 2870 | 118 | | Domestic | 10 2860 |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.²) | Q (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| | Bedrock? | | | | | Chem. analysis available |
| 27<br>2953 | Bedrock | Sandstone | 40 | 90<br>(K = 2) | 2 | No recovery |
| | | | | | | Chem. analysis available |
| | | | | | | Chem. analysis available |
| 25<br>3060 | Bedrock | Fractured Sandstone | 50 | 400<br>(K = 76) | 9 | Recovery data |
| | Bedrock | Sandstone | | | | |
| 20<br>3010 | Bedrock | Sandstone | 90 | | | Pumped at 5 qpm |
| | Bedrock | | | | | Chem. analysis available |
| 15<br>3030 | Bedrock | Sandstones | 90 | 550<br>(K = 6) | 24 | Recovery date |
| 27<br>3033 | Bedrock | Fractured Shale Siltstones | 63 | 940<br>(K = 14) | 27 | |
| | Bedrock | | | | | Chem. analysis available |
| | Bedrock | | | | | Chem. analysis available |
| | | | | | | Chem. analysis available |
| | Bedrock | | | | | Chem. analysis available |
| | Bedrock | | | | | |
| | Bedrock | | | | | Chem. analysis available |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| 19 | 8-17-35-24W4 | 3050 | 90 | 70 - 90 | Stock | 30<br>3020 |
| 20 | 1-18-35-24W4 | 3045 | 65 | | | 40<br>3005 |
| 21 | 15-19-35-24W4 | 2950 | 15 | | Stock | 3<br>2947 |
| 22 | 2-20-35-24W4 | 3000 | 80 | 48 - 80 | Stock | 41.5<br>2958 |
| 23 | 14-20-35-24W4 | 2920 | 96 | 71 - 96 | Domestic | 35<br>2885 |
| 24 | NW-20-35-24W4 | 2890 | 30 | | | Flowing<br>2890 + |
| 25 | 8-21-35-24W4 | 2875 | 58 | | Domestic | 22<br>2853 |
| R.C.A. #77-4 | 13-21-35-24W4 | 2870 | 150 | | Testhole | Flows<br>2870 + |
| 26 | 12-22-35-24W4 | 2910 | 132 | 112 - 132 | Stock | 40<br>2870 |
| 27 | 4-23-35-24W4 | 2900 | 60 | | | 9<br>2891 |
| 28 | 15-24-35-24W4 | 3040 | 230 | 190 - 230 | Domestic | 160<br>2880 |
| 29 | 1-26-35-24W4 | 3060 | 286 | | Domestic | 50<br>3010 |
| 30 | 5-26-35-24W4 | 3085 | 260 | | Domestic stock | 120<br>2965 |
| 31 | 5-26-35-24W4 | 3085 | 250 | | Domestic | 191<br>2894 |
| 32 | 13-26-35-24W4 | 3115 | 240 | 186 - 240 | Domestic stock | 143<br>2972 |
| 33 | 13-26-35-24W4 | 3115 | 158 | | | |
| 33.5 | 11-28-35-24W4 | 2915 | 160 | 145 | Domestic stock | 20<br>2895 |
| 34 | 2-29-35-24W4 | 2950 | 81 | 70 - 81 | Stock | 60<br>2890 |
| 35 | 8-29-35-24W4 | 2885 | 140 | 120 - 140 | Domestic | 23 |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.$^2$) | $Q_{20}$ (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| 35<br>3015 | Bedrock | Sandstone (Coal?) | 55 | 300<br>(K = 18) | 8 | Chem. analysis available |
| 37<br>2963 | Bedrock | Sandstone | 30 | 28,610<br>(?) | 407 | Chem. analysis available |
| 45<br>2875 | Bedrock | Sandstone | 50+ | 1635<br>(K = 65) | 39 | |
| <br>1327<br>2738 | Bedrock<br>? | Sand, Gravel<br>Sandstone | | | | Chem. analysis available |
| 28<br>2882 | Bedrock | Sandstone, Siltstone (fractured) | 60 | 7330<br>(K = 163) | 208 | Chem. analysis available |
| 43<br>2997 | Bedrock | Sandstone | 60 | 150<br>(K = 2.8) | 4 | |
| 19<br>3041 | Bedrock | Shale<br>no aquifers | | | | 1 gpm<br>well abandoned |
| 19<br>3066 | Bedrock | Shale<br>Siltstones | 120 | 20<br>(K = 2) | 1 | No log available |
| 25<br>3060 | Bedrock | Sandstone | 50 | | | |
| 55<br>3060 | Bedrock | Sandstone | 85 | 3960<br>(K = 43) | 160 | |
| | Bedrock | | | | | Chem. analysis available |
| 45<br>2870 | Bedrock | Fractured shale, coal | 130 | 50<br>(K = 4) | 3 | Recovery data |
| 14<br>2936 | Bedrock | Sandstone | 15+ | 1310<br>(K = 66) | 9 | Chem. analysis available |
| 117<br>2768 | Bedrock | Sandstone | 110 | 13,080<br>(K = 174) | 680 | |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| | | | | | | 2862 |
| 36 | 2-30-35-24W4 | 2980 | 60 | 40 - 60 | Domestic | 39 2941 |
| 37 | 4-30-35-24W4 | 3010 | 110 | | Domestic | 55 2955 |
| 38 | 4-31-35-24W4 | 3020 | 50 | | Domestic | 30 2990 |
| 39 | NE-31-35-24W4 | 2975 | 146 | 106 - 146 | Stock | 65 2910 |
| 40 | NW-31-35-24W4 | 3030 | 96 | | | 35 2995 |
| 41 | 12-32-35-24W4 | 2930 | 80 | | | 20 2910 |
| 42 | 9-33-35-24W4 | 3025 | 60 | | Shothole | Flowing 3025 + |
| 43 | 1-34-35-24W4 | 3095 | 160 | 130 - 160 | Domestic stock | 121 2974 |
| 44 | 1-34-35-24W4 | 3095 - | 135 | | Domestic stock | 100 2995 |
| 45 | 4-34-35-24W4 | 3010 | 70 | 52 - 70 | Domestic stock | 42 2968 |
| 46 | 12-35-35-24W4 | 3110 | 215 | | Domestic | |
| 47 | 1-36-35-24W4 | 2957 | | | Shothole | Flowing 2957 + |
| 48 | SE-36-35-24W4 | 3025 | 3 | | Spring | 3 3022 |
| 49 | 12-1-35-25W4 | 3095 | 96 | | Domestic | 50 3045 |
| 50 | 12-2-35-25W4 | 3035 | | | Shothole | Flowing 3035 + |
| 51 | 9-3-35-25W4 | 3030 | | | Shothole | Flowing 3030 + |
| 52 | 4-9-35-25W4 | 3025 | 115 | 100 - 115 | Domestic | 30 2995 |
| 53 | 1-10-35-25W4 | 3030 | 98 | 84 - 98 | Domestic stock | 35 2995 |
| 54 | 14-12-35-25W4 | 3130 | 150 | | Domestic | 20 3110 |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.$^2$) | Q (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| 36<br>2944 | Bedrock | Sandstone shale | 15 + | 29,930 | 190 | |
| | Bedrock | ? | | | | Chem. analysis available |
| | Drift? | | | | | Chem. analysis available |
| 36<br>2939 | Bedrock | Sandstone | 75 | 3120<br>1950 | 110 | Recovery data |
| | | | | | | Chem. analysis available |
| | | | | | | Chem. analysis available |
| 51<br>3044 | Bedrock | Sandstone | 35 + | 23,880<br>(K = 220) | 396 | |
| 35<br>2975 | Bedrock | Sandstone | 25 + | 53,990 | 640 | Recovery data |
| | Bedrock | | | | | Chem. analysis available |
| | Drift | | | | | Chem. analysis available |
| 85<br>2940 | Bedrock | Shale, Sandstone | 70 + | | | Chem. analysis available |
| 82?<br>2948 | Bedrock | Sandstone | 50 | | | |
| | Bedrock | | | | | Chem. analysis available |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| 55 | 2-13-35-25W4 | 3140 | 65 | | Domestic stock | 45 3095 |
| 56 | 13-13-35-25W4 | 3120 | 220 | 180 - 220 | Domestic stock | 115 3005 |
| 57 | 13-13-35-25W4 | 3120 | 205 | 170 - 205 | Domestic stock | 120 3000 |
| 58 | 13-13-35-25W4 | 3120 | 290 | | Domestic stock | 140 2980 |
| 59 | 4-15-35-25W4 | 3100 | 102 | 60 - 102 | Domestic stock | 42 3058 |
| 60 | 4-15-35-25W4 | 3100 | 60 | | Stock | 27 3073 |
| 61 | 1-17-35-25W4 | 3075 | 125 | 87 - 125 | Domestic stock | 72 3003 |
| 62 | 15-20-35-25W4 | 3150 | 158 | 98 - 158 | Domestic stock | 104 3046 |
| 63 | 15-21-35-25W4 | 3150 | 90 | 65 - 90 | Domestic stock | 23 3127 |
| 64 | 16-21-35-25W4 | 3120 | 78 | | Stock | 15 3105 |
| 65 | 16-22-35-25W4 | 3150 | 205 | | | 100 3050 |
| 66 | 8-23-35-25W4 | 3075 | 130 | 110 - 130 | Domestic stock | 85 2990 |
| 67 | SE-25-35-25W4 | 3025 | 125 | | Domestic | 120 2905 |
| 68 | 4-25-35-25W4 | 3065 | 132 | | Domestic | 120 2945 |
| 69 | 2-27-35-25W4 | 3190 | 183 | 118 - 183 | Domestic stock | 87 3103 |
| 70 | 2-27-35-25W4 | 3190 | 220 | 180 - 220 | Domestic | 159 3031 |
| 71 | 9-27-35-25W4 | 3125 | 164 | 144 - 164 | Domestic stock | 123 3002 |
| 72 | 2-28-35-25W4 | 3180 | 115 | 90 - 115 | Domestic stock | 52 3128 |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.²) | $Q_{20}$ (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| 32<br>3088 | Bedrock | Sandstones | 85 | 240<br>(K = 3) | 10 | |
| 24<br>3096 | Bedrock | Sandstones | 80 | 50 | 2 | Recovery data |
| | Bedrock | | | | | Chem. analysis available |
| 38<br>3062 | Bedrock | Sandstone, coals | 50 + | | | Chem. analysis available |
| | Bedrock<br>? | | | | | Chem. analysis available |
| 84<br>2991 | Bedrock | Fractured shale | 45 | 370<br>(K = 10.6) | 8 | Chem. analysis available<br>Recovery data |
| 80<br>3070 | Bedrock | Sandstone | 50 | 180<br>(K = 4.5) | 4 | |
| 31<br>3119 | Bedrock | Sandstone coal | 50 | 3060<br>(K = 50) | 73 | |
| 25<br>3050 | Bedrock | Sandstone | 40 | 4670<br>(K = 40) | 88 | Recovery data<br>Chem. analysis available |
| | Bedrock | | | | | Chem. analysis available |
| | | | | | | Chem. analysis available |
| 95<br>3095 | Bedrock | Sandstone coal | 90 | 245<br>(K = 3) | 10 | Chem. analysis available |
| 4<br>3186 | Bedrock | Sandstone coals | 55 + | | >20 | |
| 24<br>3101 | Bedrock | Sandstone | 35 + | 4670<br>(K = 29) | >78 | Recovery data |
| 28<br>3152 | Bedrock | Fractured siltstone, shale | 45 | 102<br>(K = 1.7) | > 2 | |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| 73 | 3-29-35-25W4 | 3150 | 17 | | | 4<br>3146 |
| 74 | 3-30-35-25W4 | 3050 | 8002 | | Oil well or gas | |
| 75 | SW-32-35-25W4 | 3190 | Spring | | Stock | 3190 + |
| 76 | 6-34-35-25W4 | 3089 | 3275 | | Oil or Gas Well | |
| 77 | 12-34-35-25W4 | 3175 | 200 | | Domestic | 100<br>3075 |
| 78 | 12-35-35-25W4 | 3075 | 220 | 160 - 220 | Domestic | 94<br>2981 |
| 79 | NE-36-35-25W4 | 3035 | 118 | | Domestic | 20<br>3015 |
| 81 | 4-2-36-24W4 | 3150 | 100 | 80 - 100 | Domestic stock | 79<br>3071 |
| 82 | 13-2-36-24W4 | 3100 | 300 | 240 - 300 | Domestic | 204<br>2896 |
| 83 | 13-2-36-24W4 | 3100 | 190 | 50 - 190 | Domestic stock | 92<br>3008 |
| 84 | SE-3-36-24W4 | 3100 | 257 | | | 157<br>2943 |
| 85 | SE-4-36-24W4 | 3035 | 70 | 67 - 70 | Stock | 50<br>2985 |
| 86 | 13-4-36-24W4 | 3010 | 50 | | | 40<br>2970 |
| 87 | 16-4-36-24W4 | 3030 | ? | | Shothole | 0<br>3030 + |
| 88 | 13-5-36-24W4 | 2925 | 65 | 60 - 65 | Domestic | 0<br>2925 + |
| 89 | 13-5-36-24W4 | 2920 | 60 | | Shothole | 0<br>2920 + |
| R.C.A. #77-3 | 8-6-36-24W4 | 2920 | 110 | | Testhole | |
| 90 | 11-6-36-24W4 | 2925 | 62 | 42 - 62 | Domestic stock | 24<br>2901 |
| 91 | 14-6-36-24W4 | 2950 | 93 | 70 - 93 | Domestic | 70 |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.²) | $Q_{20}$ (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| | | | | | | E-Log available 600' + |
| | | | | | | E-Log available 300' + |
| 55<br>3120 | Bedrock | Sandstone, Shale | 80 | ? 500<br>(K = 42) | 20 | |
| 45<br>3030 | Bedrock | Fractured Siltstone, Shale, coal | 115 | 25<br>(K = 2.5) | 1 | |
| 24<br>3126 | Bedrock | Sandstone | 15 + | 14,250<br>(K = 356) | 100 | |
| 18<br>3082 | Bedrock | Sandstone | 90 + | 140<br>(K = 4.7) | 6 | |
| 15<br>3085 | Bedrock | Sandstone Siltstone Shale, coal | 90 + | 70<br>(K = 3.5) | 3 | Recovery data |
| | Bedrock | | | | | Chem. analysis available |
| 28<br>3007 | Bedrock | Sandstone | 15 + | 730<br>(K = 12) | 5 | |
| 59<br>2866 | Bedrock<br>? | Fractured shale | 60 + | 3660 | 104 | Chem. analysis available |
| 54<br>2866 | | Sandstone | | | | |
| 21<br>2904 | Bedrock | Sandstone | 30 | 1190<br>(K = 24) | 17 | |
| 17<br>2933 | Bedrock | Sandstone shale | 15 | 1560<br>(K = 30) | 11 | |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| | | | | | | 2880 |
| 92 | 16-6-36-24W4 | 2925 | 90 | 76 - 90 | Domestic | 17<br>2908 |
| 93 | 16-5-36-24W4 | 3010 | 130 | 120 - 130 | Industrial | 60<br>2950 |
| 94 | 16-6-36-24W4 | 2925 | 71 | 60 - 71 | Domestic | 30<br>2895 |
| 95 | 16-6-36-24W4 | 2925 | 81 | 61 - 81 | Domestic | 17<br>2908 |
| 96 | 16-6-36-24W4 | 2925 | 50 | 40 - 50 | Domestic | 5<br>2920 |
| 97 | 16-6-36-24W4 | 2925 | 87 | 80 - 87 | Domestic | 20<br>2905 |
| 98 | 16-6-36-24W4 | 2925 | 75 | 55 - 75 | Domestic | 21<br>2904 |
| 99 | 7-7-36-24W4 | 2965 | | | Domestic | |
| 100 | 5-9-36-24W4 | 2985 | 60 | 48 - 60 | Domestic | 30<br>2955 |
| 101 | 5-9-36-24W4 | 2985 | 74 | 44 - 74 | Domestic stock | 32<br>2953 |
| 102 | 8-10-36-24W4 | 3090 | 100 | | Domestic | 90<br>3000 |
| 103 | 13-11-36-24W4 | 3060 | 140 | 103 - 140 | Domestic stock | 34<br>3026 |
| 104 | 5-12-36-24W4 | 3040 | 80 | | Domestic stock | 50<br>2990 |
| 105 | NE-12-36-24W4 | 3100 | 61 | 34 - 61 | Domestic stock | 18<br>3082 |
| 106 | 5-14-36-24W4 | 3060 | 100 | | | |
| 107 | 3-15-36-24W4 | 3085 | 255 | 120 - 255 | Domestic stock | 78<br>3007 |
| 108 | NW-16-36-24W4 | 3080 | 127 | 100 - 127 | Domestic stock | 99<br>2981 |
| 109 | 4-18-36-24W4 | 2965 | 108 | | Domestic | 60<br>2905 |
| 110 | 4-18-36-24W4 | 2965 | 80 | 60 - 80 | Domestic | 42<br>2923 |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.²) | $Q_{20}$ (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| 59<br>2866 | Bedrock | Sandstone | 65 | 1220<br>(K = 80) | 38 | Chem. analysis available |
| 60<br>3050 | Bedrock | ? | ? | 625<br>(K = 63) | | |
| 60<br>2865 | Bedrock | Sandstone | 35+ | 1220<br>(K = 49) | 20 | Chem. analysis available |
| 58<br>2867 | Bedrock | Siltstone | 55+ | >36,620 | >56 | |
| 30<br>2895 | Bedrock | Sandstone | 40+ | 150<br>(K = 15) | 3 | Recovery data |
| 56<br>2869 | Bedrock | Sandstone | 60+ | 1470 | 42 | |
| 57<br>2868 | Bedrock | Sandstone | 50+ | 5707<br>(K = 260) | 135 | |
| | | | | | | Chem. analysis available |
| 9<br>2976 | Bedrock | Sandstone | 25+ | 3120<br>(K = 27) | >37 | Chem. analysis available |
| 14<br>2971 | Bedrock | Sandstone | 35+ | 3800<br>(K = 35) | >63 | |
| 18<br>3042 | Bedrock | Sandstone shale, coals | 85 ? | 60<br>(K = 12.4) | 2 | Chem. analysis available |
| 30<br>3070 | Bedrock | Sandstone | 35 | 910<br>(K = 21) | 15 | |
| | | | | | | Chem. analysis available |
| 24<br>3061 | Bedrock | Sandstone | 65+ | 2980<br>(K = 32.4) | 92 | |
| 15<br>3065 | Bedrock | Sandstone | 20+ | 87,195<br>(K = 1744) | 8.27 | |
| | | | | | | Chem. analysis available |
| 28<br>2937 | Bedrock | Shale, siltstone | 30 | 6810<br>(K = 57) | 97 | Recovery data |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| 111 | 12-18-36-24W4 | 2980 | 80 | | Domestic stock | 50<br>2930 |
| 112 | 12-18-36-24W4 | 2980 | 145 | 117 - 145 | Domestic stock | 84<br>2896 |
| 113 | NE-18-36-24W4 | 3030 | 47 | | | 40<br>2990 |
| 114 | 14-19-36-24W4 | 2983 | 60 | | Shothole | 0<br>2983 + |
| 115 | 14-19-36-24W4 | 2984 | 60 | | Shothole | 0<br>2984 + |
| 116 | 14-19-36-24W4 | 2983 | 40 | | Shothole | 0<br>2983 + |
| 117 | 14-19-36-24W4 | 2994 | 45 | | Shothole | 0<br>2994 + |
| 118 | 15-19-36-24W4 | 2990 | 60 | | Shothole | 0<br>2990 + |
| 119 | 16-19-36-24W4 | 2991 | 40 | | Shothole | 0<br>2991 + |
| 120 | 16-19-36-24W4 | 2997 | 40 | | Shothole | 0<br>2997 + |
| 121 | 16-19-36-24W4 | 2997 | | | Shothole | 0<br>2997 + |
| 122 | 4-20-36-24W4 | 3035 | 90 | | Domestic | 35<br>3000 |
| 123 | 12-20-36-24W4 | 3025 | 165 | | Domestic | 60<br>2965 |
| 124 | 13-20-36-24W4 | 3013 | 47 | | Shothole | 0<br>3013 + |
| 125 | NW-20-36-24W4 | 3025 | 90 | | Testhole | 60<br>2965 |
| 126 | 5-21-36-24W4 | 3145 | 180 | 157 - 180 | Domestic | 135<br>3010 |
| 127 | 14-21-36-24W4 | 3165 | 200 | 130 - 200 | Domestic stock | 130<br>3135 |
| 128 | 4-22-36-24W4 | 3133 | 5867 | | Oil or gas well | |
| 129 | 9-22-36-24W4 | 3120 | 130 | | Domestic | 90<br>3030 |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.²) | $Q_{20}$ (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| 11<br>2969 | Bedrock | Shale | 55 | 2280<br>>19 | 59 | Recovery data<br>Chem. analysis available |
| | | | | | | Chem. analysis available |
| | | | | | | Chem. analysis available |
| 12<br>3133 | Bedrock | Sandstone | 40+ | 2190<br>(K = 48.6) | 42 | Chem. analysis available |
| 15<br>3150 | Bedrock | Sandstone shale | 65 | 290<br>K = 9.7) | 9 | E-Log available 800'+<br>Chem. analysis available |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| 130 | 14-22-36-24W4 | 3120 | 60 | | | 22<br>3098 |
| 131 | 4-23-36-24W4 | 3085 | 131 | 106 - 131 | Domestic stock | 72<br>3013 |
| 132 | 14-23-36-24W4 | 3065 | 62 | | | 30<br>3035 |
| 133 | 12-26-36-24W4 | 3060 | 110 | 79 - 110 | Domestic stock | 62<br>2998 |
| 134 | 4-27-36-24W4 | 3150 | 70 | 50 - 70 | Domestic stock | 46<br>3104 |
| 135 | 4-27-36-24W4 | 3120 | 62 | | Domestic stock | 19<br>3101 |
| 136 | 4-27-36-24W4 | 3125 | 165 | | Abandoned | |
| 136 | 4-27-36-24W4 | 3125 | 165 | | Abandoned | |
| 137 | 9-27-36-24W4 | 3050 | 140 | | Domestic | |
| 138 | 2-28-36-24W4 | 3180 | 300 | 270 - 300 | Domestic stock | 179.8<br>3000 |
| 139 | 2-28-36-24W4 | 3180 | 200 | | Domestic stock | 168<br>3012 |
| 140 | 15-28-36-24W4 | 3090 | 118 | | Domestic stock | 83<br>3007 |
| 141 | 4-29-36-24W4 | 3025 | 80 | | Domestic | 29<br>2996 |
| 142 | 4-29-36-24W4 | 3030 | 43 | | Domestic | 33<br>2997 |
| 143 | 3-30-36-24W4 | 2990 | 50 | | Stock | 0<br>2990 + |
| 144 | 8-30-36-24W4 | 3050 | 125 | | Domestic stock | 55<br>2995 |
| 145 | 8-30-36-24W4 | 3050 | 62 | | Domestic stock | 38<br>3012 |
| 146 | 1-31-36-24W4 | 3135 | 198 | 178 - 198 | Domestic | 151<br>2984 |
| 147 | 1-31-36-24W4 | 3135 | 206 | 180 - 206 | Domestic | 154<br>2981 |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.²) | Q (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| 35<br>3050 | Bedrock | Sandstone | 50 | 1230<br>(K = 23.7) | 29 | Recovery data |
| 45<br>3015 | Bedrock | Sandstone<br>siltstone | 40 | 28,670<br>(K = 956) | 544 | |
| 17<br>3133 | Bedrock | Sandstone | 15 | 9490<br>(K = 431) | 68 | |
| 50<br>3070 | Bedrock | Sandstone | 30 | 2440<br>(K = 407) | 35 | |
| 60<br>3065 | Bedrock | Shale | | | | |
| 60<br>3065 | Bedrock | Shale | | | | |
| | | | | | | Chem. analysis available |
| 15<br>3165 | Bedrock | Sandstone | 115 | 2300<br>(K = 66) | 125 | Recovery data |
| | | | | | | Chem. analysis available |
| 44<br>2981 | | | | | | |
| 40<br>2950 | Bedrock | Fractured shale | | | | |
| 45<br>3005 | Bedrock | Sandstone | 60 | 370<br>(K = 14.9) | 11 | |
| 19<br>3116 | Bedrock | Sandstone | 40+ | 13,080<br>(K = 248) | 248 | |
| 20<br>3115 | Bedrock | Sandstone | 40+ | 19,620<br>(K = 192) | 372 | |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| 148 | 8-32-36-24W4 | 3110 | 200 | 130 - 200 | Stock | 120<br>2990 |
| 149 | 9-32-36-24W4 | 3100 | 145 | | | 125<br>2975 |
| 150 | 7-33-36-24W4 | 3060 | 122 | | | 90<br>2970 |
| 151 | 12-33-36-24W4 | 3075 | 130 | 90 - 130 | Domestic | 91<br>2984 |
| 152 | 12-33-36-24W4 | 3075 | 126 | | | 30<br>3045 |
| 153 | 16-33-36-24W4 | 3040 | 105 | 91 - 105 | Stock | 70<br>2970 |
| 154 | 13-34-36-24W4 | 3025 | 80 | | | 64<br>2961 |
| 154.5 | 4-2-36-25W4 | 3100 | 43 | 24 - 43 | Stock | 18<br>3087 |
| 155 | 2-3-36-24W4 | 3085 | 123 | 32 - 123 | Stock | 30<br>3055 |
| 156 | 2-3-36-25W4 | 3100 | 74 | | | 22<br>3078 |
| 157 | NE-4-36-25W4 | 3160 | 120 | 103 - 120 | Stock | 63<br>3097 |
| 158 | 12-5-36-25W4 | 3165 | 200 | 160 - 200 | Domestic stock | 126<br>3039 |
| 159 | 12-6-36-25W4 | 3080 | 80 | | | 66<br>3014 |
| 160 | 8-7-36-25W4 | 3175 | 118 | 103 - 118 | Domestic stock | 55<br>3120 |
| 161 | SW-8-36-25W4 | 3185 | 99 | | | 40<br>3145 |
| 162 | 16-8-36-25W4 | 3275 | 155 | 133 - 155 | Domestic stock | 110<br>3165 |
| 163 | 16-8-36-25W4 | 3275 | 115 | | | |
| 164 | 16-8-36-25W4 | 3275 | 109 | | | 100<br>3175 |
| 165 | 5-9-36-25W4 | 3225 | 180 | 120 - 180 | Domestic stock | 91<br>3134 |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.²) | $Q_{20}$ (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| 59<br>3051 | Bedrock | Sandstone shale | 70 | 200<br>(K = 2.9) | 7 | Recovery data<br>Chem. analysis available |
| 45<br>3030 | Bedrock | Sandstone | 35 | 5810<br>(K = 194) | 96 | Recovery data |
| 50<br>2990 | Bedrock | Sandstone shale | 30 | 730<br>(K = 12) | 10 | |
| 19<br>3081 | Bedrock | Sandstone shale | 20 | 190<br>(K = 46.8) | 2 | |
| 28<br>3057 | Bedrock | Sandstone | 20 | 12,150<br>(K = 347) | 115 | Chem. analysis available |
| 76<br>3084 | Bedrock | Sandstone | 50 | 950<br>(K = 36.4) | 23 | Chem. analysis available |
| 100<br>3065 | Bedrock | Sandstone coal, shale | 60 | 300<br>(K = 15) | 9 | |
| 84<br>3091 | Bedrock | Sandstone shale | 55 | 5890<br>(K = 131) | 154 | |
| 68<br>3207 | Bedrock | Shale Siltstone? | 40 | 130<br>(K = 6.5) | 3 | Recovery data<br>Chem. analysis available |
| 26<br>3199 | Bedrock | Shale Siltstone | 80 | 80<br>(K = 1.4) | 3 | Chem. analysis available<br>Recovery data |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| 166 | 8-9-36-25W4 | 3175 | 54 | | Stock | 8<br>3167 |
| 167 | 9-9-36-25W4 | 3135 | 145 | 138 - 145 | Stock | <93<br>3042 |
| 168 | 12-9-36-25W4 | 3225 | 111 | | | 35<br>3190 |
| 169 | 15-10-36-25W4 | 3023 | 60 | | Shothole | 0<br>3023+ |
| 170 | 1-12-36-25W4 | 2950 | 92 | | Domestic | |
| 171 | 1-12-36-25W4 | 2950 | 110 | | Domestic | 43<br>2907 |
| 172 | 1-12-36-26W4 | 2950 | 71 | 63 - 71 | Domestic | 34<br>2916 |
| 173 | 3-12-36-25W4 | 2970 | 50 | 38 - 50 | Stock | 0<br>2970 |
| 174 | 8-12-36-25W4 | 2960 | 107 | 80 - 107 | Domestic | 43<br>2917 |
| 175 | 14-12-36-25W4 | 2965 | 107 | 95 - 107 | Domestic | 45<br>2920 |
| 176 | 14-12-36-25W4 | 2945 | 155 | 93 - 155 | Domestic | 59<br>2886 |
| 177 | 14-12-36-25W4 | 2945 | 102 | 98 - 102 | Domestic | 55<br>2800 |
| 178 | 1-13-36-25W4 | 2925 | 100 | | Domestic | 64<br>2861 |
| 179 | 1-13-36-25W4 | 2925 | 80 | 59 - 80 | Domestic | 36<br>2889 |
| 180 | 1-13-36-25W4 | 2925 | 93 | | Domestic | 15<br>2910 |
| 181 | 1-13-36-25W4 | 2925 | 98 | 88 - 98 | Domestic | 55<br>2870 |
| 182 | 6-13-36-25W4 | 2925 | 180 | 172 - 180 | Domestic | 36<br>2889 |
| 183 | 6-13-36-25W4 | 2920 | 80 | 60 - 80 | Domestic | 13<br>2907 |
| 184 | 13-14-36-25W4 | 3025 | 75 | | Domestic | 12<br>3013 |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.²) | $Q_{20}$ (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| 25<br>3150 | Bedrock | Shale<br>Fractured ? | 40 | 1470<br>(K = 49) | 28 | |
| 70<br>3065 | Bedrock | Sandstone | ? | 2680<br>(K = 72) | 38 | |
| | | | | | | Chem. analysis available |
| | | | | | | Chem. analysis available |
| 20<br>2930 | Bedrock | Sandstone | 30 | 930<br>(K = 23) | 13 | Chem. analysis available |
| 30<br>2940 | Bedrock | Sandstone | 45+ | | | Chem. analysis available |
| 38<br>2922 | Bedrock | Sandstone | 55+ | 290<br>(K = 4.8) | 8 | |
| 26<br>2939 | Bedrock | Sandstone | 55+ | 3180<br>(K = 32) | 83 | |
| 37<br>2908 | Bedrock | Sandstone | 90+ | 1820<br>(K = 30) | 78 | Chem. analysis available<br>Recovery data |
| 45<br>2900 | Bedrock | Shale | 40 | 3180 | 60 | |
| | | | | | | Chem. analysis available |
| 37<br>2888 | Bedrock | Sandstone | 35 | 53,860<br>(K = 1077) | 893 | |
| | | | | | | Chem. analysis available |
| 25<br>2900 | Bedrock | Shale<br>(fractured) | 35 | 2930<br>(K = 58.7) | 49 | Chem. analysis available |
| 75<br>2850 | Bedrock | Shale<br>(Fractured) | 135 | 340<br>(K = 6.8) | 22 | |
| 54<br>2866 | Bedrock | Shale,<br>coal | 50+ | ? 11750<br>(K = 1175) | 278 | |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| 185 | 5-15-36-25W4 | 3095 | 100 | 80 - 100 | Stock | 50<br>3045 |
| 186 | 3-16-36-25W4 | 3190 | 63 | 49 - 63 | Domestic stock | 28<br>3162 |
| 187 | 16-17-36-25W4 | 3160 | 85 | 35 - 85 | Stock | 59<br>3101 |
| 188 | 12-19-36-25W4 | 3200 | 180 | | | ? |
| 189 | 12-19-36-25W4 | 3200 | 185 | | | 90<br>3110 |
| 190 | 12-19-36-25W4 | 3200 | 126 | | Domestic | 81<br>3119 |
| 191 | 11-21-36-25W4 | 3090 | | | Shothole | 0<br>3090+ |
| 192 | 12-21-36-25W4 | 3100 | | | Shothole | 0<br>3100+ |
| 193 | 12-21-36-25W4 | 3100 | 75 | | Shothole | 0<br>3100+ |
| 194 | 8-22-36-25W4 | 3035 | 105 | 90 - 105 | Domestic stock | 62<br>2973 |
| 195 | 8-22-36-25W4 | 3000 | 122 | | Domestic stock | 30<br>2970 |
| 196 | 11-22-36-25W4 | 3025 | 190 | 153 - 190 | Domestic stock | 79<br>2946 |
| 197 | 16-22-36-25W4 | 3025 | 95 | 75 - 95 | Domestic | 40<br>2985 |
| 198 | 16-22-36-25W4 | 3015 | 94 | | Domestic | 29<br>2986 |
| R.C.A. #77-1 | 16-22-36-25W4 | 2920 | 120 | | Testhole | 0<br>2920 |
| 199 | 16-22-36-25W4 | 2935 | 190 | 145 - 190 | Domestic | 15<br>2920 |
| 200 | 4-23-36-25W4 | 3000 | 165 | 80 - 165 | Domestic | 40<br>2960 |
| 201 | 14-23-36-25W4 | 2930 | 83 | 65 - 83 | Domestic | 0<br>2930+ |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.²) | $Q_{20}$ (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| 39<br>3056 | Bedrock | Siltstone shale | 45+ | | >11 | Chem. analysis available |
| 16<br>3174 | Bedrock | Sandstone | 25+ | 1720<br>(K = 23) | 20 | |
| 23<br>3137 | Bedrock | Sandstone Shale | 10 | 210<br>(K = 13) | 2 | Recovery data |
| | | | | | | Chem. analysis available |
| | Drift | | | | | Chem. analysis available |
| 53<br>2982 | Bedrock | Siltstone (fractured) | 35 | 160<br>(K = 11.4) | 3 | Recovery data<br>Chem. analysis available |
| | | | | | | Chem. analysis available |
| 20<br>3005 | Bedrock | Siltstone sandstone | 105 | 42<br>(K = 1.1) | 2 | Chem. analysis available |
| 23<br>3002 | Bedrock | Sandstone shale (fractured) | | | | Chem. analysis available |
| | | | | | | Chem. analysis available |
| 112<br>2808 | Bedrock | Sand sandstone | 115 | | | |
| 142<br>2793 | Bedrock | Shale (fractured) | 150+ | 50<br>(K = 1) | 4 | Recovery data<br>Chem. analysis available |
| <75 | Bedrock | Coal, shale | 120 | 1470 | 83 | Chem. analysis available |
| 62<br>2868 | Bedrock | Shale siltstone ? | 75+ | 840<br>(K = 42) | 30 | Recovery data<br>Chem. analysis available |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| 202 | 14-23-36-25W4 | 2930 | 85 | 78 - 85 | Domestic | 0<br>2930 + |
| 203 | 2-24-36-25W4 | 2925 | 60 | 46 - 60 | Domestic | 2 ?<br>2923 |
| 204 | 2-24-36-25W4 | 2960 | 100 | | Domestic | 60 ?<br>2900 |
| 205 | 2-24-36-25W4 | 2945 | 90 | 70 - 90 | Domestic | 21<br>2924 |
| 206 | NW-24-36-25W4 | 2970 | 95 | 65 - 95 | Domestic stock | 38<br>2932 |
| 207 | 3-25-36-25W4 | 2970 | 85 | 75 - 85 | Domestic stock | 26<br>2944 |
| 208 | 3-25-36-25W4 | 2975 | 105 | 40 - 105 | Stock | 30<br>2945 |
| 209 | 2-26-36-25W4 | 2950 | 105 | | Domestic | 20<br>2930 |
| 210 | 2-26-36-25W4 | 2960 | 60 | 59 - 60 | Domestic | 30<br>2930 |
| 211 | 3-26-36-25W4 | 2940 | 80 | 60 - 80 | Domestic | 13<br>2927 |
| 212 | 3-26-36-25W4 | 2930 | 55 | 40 - 55 | Domestic | 0<br>2930 |
| 213 | 10-26-36-25W4 | 3015 | 90 | | Domestic stock | 46<br>2969 |
| 214 | 10-26-36-25W4 | 3015 | 75 | | Domestic stock | 55<br>2960 |
| 215 | 10-26-36-25W4 | 3015 | 15 | | Domestic stock | 10<br>3005 |
| 216 | 1-27-36-25W4 | 3030 | 122 | | Domestic | |
| 217 | 4-28-36-25W4 | 3093 | 100 | | Shothole | 0<br>3093 + |
| 218 | 4-28-36-25W4 | 3107 | 100 | | Shothole | 0<br>3107 + |
| 219 | 13-28-36-25W4 | 3085 | 80 | | Domestic stock | 55<br>3030 |
| 220 | 8-29-36-25W4 | 3067 | 80 | | Shot hole | 0<br>3067 + |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.$^2$) | $Q_{20}$ (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| 75<br>2855 | Bedrock | Fractured shale | 80+ | | 30 | |
| 40<br>2885 | Bedrock | Sandstone | 50+ | 3270<br>(K = 109) | 77 | Chem. analysis available |
| 25<br>2920 | Bedrock | Sandstone | 70 | | 20 | Chem. analysis available<br>Chem. analysis available |
| 41<br>2929 | Bedrock | Sandstone | 45 | 3970<br>(K = 120) | 85 | |
| 35<br>2935 | Bedrock | Sandstone siltstone | 50 | 3924<br>(K = 98) | 93 | Recovery data |
| 60 ?<br>2915 | Bedrock | Sandstone | | | | Chem. analysis available |
| 60<br>2900 | Drift | Gravel | 25 | 8130<br>(K = 1626) | 96 | |
| 53<br>2887 | Bedrock | Shale Siltstone | 60 | 690<br>(K = 23) | 20 | Pump test data<br>Chem. analysis available |
| 37<br>2803 | Bedrock | Shale Siltstone | 50+ | 1300<br>(K = 81) | 28 | |
| 48<br>2967 | Bedrock | Siltstone (shale) | 40 | 1150<br>(K = 29) | 22 | |
| 55<br>2960 | Bedrock | Shale | 15 | 4400<br>(K = 220) | 31 | Chem. analysis available |
| 90<br>2995 | Drift | | | | | |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| 221 | 8-29-36-25W4 | 3070 | 100 | | Shothole | 0<br>3070 + |
| 222 | 13-29-36-25W4 | 3093 | 45 | | Shothole | 0<br>3093 + |
| 223 | 14-29-36-25W4 | 3100 | 150 | | Shothole | 0<br>3100 + |
| 224 | 15-29-36-25W4 | 3100 | 60 | | Shothole | 0<br>3100 + |
| 225 | 15-29-36-25W4 | 3100 | 100 | | Shothole | 0<br>3100 + |
| 226 | 15-30-36-25W4 | 3125 | 37 | 23 - 37 | Domestic stock | 19<br>3106 |
| 227 | 1-31-36-25W4 | 3160 | 120 | 110 - 120 | Domestic stock | 61<br>3099 |
| 228 | 5-31-36-25W4 | 3240 | 175 | | Domestic | 110<br>3130 |
| 229 | 11-31-36-25W4 | 3123 | 50 | | Shothole | 0<br>3123 + |
| 230 | 11-31-36-25W4 | 3124 | 50 | | Shothole | 0<br>3124 + |
| 231 | 14-31-36-25W4 | 3127 | 45 | | Shothole | 0<br>3127 + |
| 232 | 14-31-36-25W4 | 3106 | 100 | | Shothole | 0<br>3106 + |
| 233 | 14-31-36-25W4 | 3115 | ? | | Shothole | 0<br>3115 + |
| 234 | 15-31-36-25W4 | 3112 | 50 | | Shothole | 0<br>3112 + |
| 235 | 15-31-36-25W4 | 3116 | 50 | | Shothole | 0<br>3116 + |
| 236 | 9-31-36-25W4 | 3081 | 100 | | Shothole | 0<br>3081 |
| 237 | 16-31-36-25W4 | 3077 | 100 | | Shothole | 0<br>3077 + |
| 238 | 16-31-36-25W4 | 3074 | 50 | | Shothole | 0<br>3074 + |
| 239 | 4-32-36-25W4 | 3145 | 135 | 110 - 135 | Domestic stock | 58<br>3087 |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.²) | $Q_{20}$ (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| 10<br>3115 | Bedrock | Sandstone siltstone | 10 | 380<br>(K = 26) | 2 | |
| 58<br>3102 | Bedrock | Siltstone shale | 50 | 1870<br>(K = 31) | 44 | |
| 20<br>3220 | Bedrock | Sandstone | 60 | 160<br>(K = 33) | 5 | |
| | | | | | | 0 - 50 clay |
| | | | | | | 0 - 50 clay |
| | | | | | | 0 - 50 clay and rocks |
| | | | | | | 0 - 50 clay |
| 24<br>3121 | Bedrock | Sandstone shale | 70 | 523<br>(K = 32.7) | 17 | Recovery data |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| 240 | 13-32-36-25W4 | 3077 | 50 | | Shothole | 0<br>3077 + |
| 241 | 13-32-36-25W4 | 3067 | 50 | | Shothole | 0<br>3067 + |
| 242 | 13-32-36-25W4 | 3066 | 40 | | Shothole | 0<br>3066 + |
| 243 | 13-32-36-25W4 | 3067 | 150 | | Shothole | 0<br>3067 + |
| R.C.A. #77-2 | 15-33-36-25W4 | 3125 | 80 | 50 - 80 | Testhole | 18<br>3107 |
| 244 | 15-34-36-25W4 | 2969 | 60 | | Shothole | 0<br>2969 + |
| 245 | 13-35-36-25W4 | 3021 | 52 | | Shothole | 0<br>3021 + |
| 246 | 15-35-36-25W4 | 3060 | 109 | 75 - 109 | Stock | 70<br>2990 |
| 247 | 15-35-36-25W4 | 3060 | 230 | | Stock | 110<br>2950 |
| 248 | 15-35-36-25W4 | 3055 | 265 | | Domestic | 105<br>2950 |
| 249 | 13-11-36-26W4 | 3125 | 121 | | Stock | 45<br>3080 |
| 250 | 1-14-36-26W4 | 3070 | 60 | | Domestic | 25<br>3045 |
| 251 | 12-14-36-26W4 | 3150 | 80 | 70 - 80 | Domestic | 28<br>3122 |
| 252 | 12-14-36-26W4 | 3160 | 102 | | Domestic | 50<br>3110 |
| 253 | 15-13-36-26W4 | 3120 | 75 | | Shothole | 0<br>3120 + |
| 254 | 2-23-36-26W4 | 3079 | 75 | | Shothole | 0<br>3079 + |
| 255 | 2-23-36-26W4 | 3115 | 75 | | Shothole | 0<br>3115 + |
| 256 | 2-23-36-26W4 | 3115 | 75 | | Shothole | 0<br>3115 + |
| 257 | 10-23-36-26W4 | 3117 | 75 | | Shothole | 0<br>3117 + |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.²) | Q (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| | | | | | | 0 - 50 clay |
| | | | | | | 0 - 50 clay |
| | | | | | | 0 - 40 clay |
| 54<br>3071 | Bedrock | Sandstone | 45 | | | |
| | | | | | | 0 - 60<br>sand & gravel |
| 63<br>2997 | Bedrock | Sandstone<br>siltstone<br>coal | 30 | 19,620<br>(K = 654) | 279 | |
| 38<br>3022 | Bedrock | Sandstone | 115 | 575<br>(K = 73) | 31 | |
| 35<br>3020 | Bedrock | Sandstone | | | | |
| 35<br>3090 | Bedrock | Sandstone | 65 | 13,080<br>(K = 409) | 403 | Chem. analysis available |
| >60 | Drift | Sand<br>gravel | 30 | 860<br>(K = 86) | 12 | |
| 18<br>3132 | Bedrock | Sandstone | 45 | 410<br>(K = 23) | 9 | |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| 258 | 10-23-36-26W4 | 3117 | 75 | | Shothole | 0<br>3117+ |
| 259 | 2-24-36-26W4 | 3125 | 50 | | Shothole | 0<br>3125+ |
| 260 | 2-25-36-26W4 | 3079 | | | Shothole | 0<br>3079+ |
| 261 | 2-25-36-26W4 | 3115 | | | Shothole | 0<br>3115+ |
| 262 | 3-25-36-26W4 | 3110 | 60 | | Shothole | 0<br>3110+ |
| 263 | 13-25-36-26W4 | 3115 | 30 | | Shothole | 0<br>3115+ |
| 264 | 13-25-36-26W4 | 3115 | 60 | | Shothole | 0<br>3115+ |
| 265 | 13-25-36-26W4 | 3120 | 75 | | Shothole | 0<br>3120+ |
| 266 | 15-25-36-26W4 | 3135 | 45 | | Shothole | 0<br>3135+ |
| 267 | 15-25-36-26W4 | 3135 | 75 | | Shothole | 0<br>3135+ |
| 268 | 16-25-36-26W4 | 3160 | 140 | | Domestic stock | 40<br>3120 |
| 269 | 16-25-36-26W4 | 3160 | 130 | | Domestic stock | 50<br>3110 |
| 270 | 16-25-36-26W4 | 3160 | 230 | 177 - 230 | Domestic stock | 130<br>3030 |
| 271 | 8-26-36-26W4 | 3093 | 60 | | Shothole | 0<br>3093+ |
| 272 | 13-26-36-26W4 | 3119 | 80 | | Shothole | 0<br>3119+ |
| 273 | 13-26-36-26W4 | 3122 | 30 | | Shothole | 0<br>3122+ |
| 274 | 16-26-36-26W4 | 3115 | 150 | | Shothole | 0<br>3115+ |
| 275 | 1-27-36-26W4 | 3120 | 180 | | Shothole | 0<br>3120+ |
| 276 | 9-27-36-26W4 | 3110 | 80 | | Shothole | 0<br>3110+ |
| 277 | 10-35-36-26W4 | 3160 | 280 | | Domestic stock | 60<br>3100 |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.²) | Q (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| 35<br>3085 | Bedrock | Sandstone<br>shale | | | | |
| 35<br>3100 | Bedrock | Sandstone<br>shale | | | | |
| 48<br>3112 | Bedrock | Siltstone<br>coals | 95 | 350<br>(K-27) | 16 | Chem. analysis available<br>Recovery data |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| 278 | 14-35-36-26W4 | 3130 | 94 | 82 - 94 | Stock | 68(?)<br>3062 |
| 279 | SW-36-36-26W4 (6) | 3190 | 75 | | | 30<br>3160 |
| 280 | 15-36-36-26W4 | 3215 | 125 | | Domestic | 75<br>3140 |
| 281 | 1-4-37-24W4 | 3025 | 90 | 65 - 90 | Domestic | 60<br>2965 |
| 282 | SE-6-37-24W4 | 3060 | 135 | | Stock | 75<br>2985 |
| 283 | 16-7-37-24W4 | 2975 | 320 | 297 - 320 | Domestic stock | 150<br>2825 |
| 284 | 1-18-37-24W4 | 2930 | 240 | 200 - 240 | Domestic stock | 190<br>2740 |
| 285 | 1-1-37-25W4 | 3165 | 242 | 200 - 242 | Domestic stock | 140<br>3025 |
| 286 | 4-1-37-25W4 | 3030 | 70 | | Domestic | 14<br>3016 |
| 287 | 16-2-37-25W4 | 3140 | 180 | | Domestic | 120<br>3020 |
| 288 | 2-3-37-25W4 | 3000 | 80 | | Stock | 0<br>3000+ |
| 289 | 9-3-37-25W4 | 3080 | 125 | 102 - 125 | Domestic stock | 105<br>2975 |
| 290 | 12-3-37-25W4 | 3040 | 110 | 80 - 110 | Industrial | 70<br>2970 |
| 291 | 9-4-37-25W4 | 3075 | 165 | 104 - 165 | Domestic | 95<br>2980 |
| 292 | 5-5-37-25W4 | 3070 | 50 | | Shothole | 0<br>3070+ |
| 293 | 5-5-37-25W4 | 3090 | 50 | | Shothole | 0<br>3090+ |
| 294 | 1-6-37-25W4 | 3074 | 50 | | Shothole | 0<br>3074+ |
| 295 | 1-6-37-25W4 | 3075 | 50 | | Shothole | 0<br>3075+ |
| 296 | 1-6-37-25W4 | 3082 | 50 | | Shothole | 0<br>3082+ |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.²) | $Q_{20}$ (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| 82<br>3048 | Bedrock | Shale (fractured?) | 20 | 630 | 6 | |
| 65<br>2960 | Bedrock | Sandstone | 25 | 19,690<br>(K = 492) | 233 | Chem. analysis available |
| 52<br>2923 | Bedrock | Siltstone shale, coal | 200 | 1170<br>(K = 20) | 111 | |
| 108<br>2822 | Bedrock | Sandstone | 35 | 730<br>(K = 18.3) | 12 | |
| 20<br>3145 | Bedrock | Sandstone siltstone | 23 | 2950<br>(K = 42) | 32 | |
| | | | | | | Chem. analysis available |
| | | | | | | Chem. analysis available |
| 90<br>2990 | Bedrock | Shale fractured | 15 | 2625<br>(K = 66) | 19 | |
| 45<br>2995 | Bedrock | Siltstone | 40 | 13,080 | 248 | No drawdown |
| 88<br>2987 | Bedrock | Siltstone sandstone coal | 65 | 13,080 | | No drawdown |
| | | | | | | 0 - 50 till |
| | | | | | | 0 - 50 till |
| | | | | | | 0 - 50 till |
| | | | | | | 0 - 50 till |
| | | | | | | 0 - 50 till |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| 297 | 1-6-37-25W4 | 3076 | 80 | | Shothole | 0<br>3076 + |
| 298 | 1-6-37-25W4 | 3067 | 50 | | Shothole | 0<br>3067 + |
| 299 | 1-6-37-25W4 | 3082 | 50 | | Shothole | 0<br>3082 + |
| 300 | 1-6-37-25W4 | 3086 | 50 | | Shothole | 0<br>3086 + |
| 301 | 2-6-37-25W4 | 3078 | 50 | | Shothole | 0<br>3078 + |
| 302 | 3-6-37-25W4 | 3100 | | | Shothole | 0<br>3100 + |
| 303 | 4-6-37-25W4 | 3113 | 50 | | Shothole | 0<br>3113 + |
| 304 | 7-6-37-25W4 | 3081 | 50 | | Shothole | 0<br>3081 + |
| 305 | 8-6-37-25W4 | 3080 | 55 | | Shothole | 0<br>3080 + |
| 306 | 13-7-37-25W4 | 3166 | 60 | | Shothole | 0<br>3166 + |
| 307 | 16-8-37-25W4 | 3105 | 150 | | Shothole | 0<br>3105 + |
| 308 | 16-8-37-25W4 | 3104 | 62 | | Shothole | 0<br>3104 + |
| 309 | 5-9-37-25W4 | 3134 | 50 | | Shothole | 0<br>3134 + |
| 310 | 5-9-37-25W4 | 3127 | 50 | | Shothole | 0<br>3127 + |
| 311 | 4-10-37-25W4 | 3065 | 100 | | Domestic | 81<br>2982 |
| 312 | 12-14-37-25W4 | 3060 | 120 | 104 - 120 | Stock | 90<br>2970 |
| 313 | 12-14-37-25W4 | 3060 | 110 | | Domestic stock | 90<br>2970 |
| 314 | 3-16-37-25W4 | 3135 | 200 | 145 - 200 | Domestic | 121<br>3014 |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.²) | $Q_{20}$ (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| | | | | | | 0 - 50 till |
| | | | | | | 0 - 50 till |
| | | | | | | 0 - 50 till |
| | | | | | | 0 - 50 till |
| | | | | | | 0 - 50 till |
| | | | | | | 0 - 50 till |
| | | | | | | 0 - 20 gravel 20-50 clay & rock |
| | | | | | | 0 - 50 clay & rock |
| 100 2965 | Drift | Drift/Bedrock Contact | | | | Chem. analysis available |
| 92 2968 | Bedrock | Fractured shale, siltstone | 25 | 3755 (K = 94) | 45 | Recovery data |
| | Bedrock | Shale, siltstone | | | | Chem. analysis available |
| 136 2993 | Bedrock | Shale sandstone | 70 | 140 (K = 7.2) | 5 | |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| 315 | 1-17-37-25W4 | 3105 | 59 | | Shot hole | 0<br>3105 + |
| 316 | 8-21-37-25W4 | 3110 | 212 | 180 - 212 | Domestic stock | 172<br>2938 |
| 317 | 6-24-37-25W4 | 2950 | 130 | 100 - 130 | Domestic stock | 20<br>2930 |
| 318 | 8-28-37-25W4 | 3025 | 100 | | Domestic | 90<br>2935 |
| 319 | 4-31-37-25W4 | 3109 | 60 | | Shothole | 0<br>3109 + |
| 320 | 14-31-37-25W4 | 3025 | 120 | | Stock | 37<br>2988 |
| 321 | 14-31-37-25W4 | 3025 | 90 | | | 50<br>2975 |
| 322 | 16-31-37-25W4 | 3000 | 150 | | Stock | 115<br>2885 |
| 323 | 13-32-37-25W4 | 2950 | 130 | 34 - 130 | Domestic | 53<br>2897 |
| 324 | 15-32-27-25W4 | 2910 | 90 | 70 - 90 | Domestic | 30<br>2880 |
| 325 | 1-1-37-25W4 | 3139 | 180 | | Shothole | 0<br>3139 + |
| 326 | 4-3-37-26W4 | 3160 | 110 | 36 - 110 | Domestic stock | 37<br>3123 |
| 327 | 4-3-37-26W4 | 3160 | 50 | | Domestic stock | 47<br>3113 |
| 328 | 8-3-37-26W4 | 3135 | 15 | | Stock | 0<br>3135 + |
| 329 | 13-3-37-26W4 | 3205 | 140 | | Domestic stock | 90<br>3115 |
| 330 | 16-4-37-26W4 | 3185 | 237 | 147 - 237 | Domesti stock | 124<br>3061 |
| 331 | 8-9-37-26W4 | 3185 | 270 | 250 - 270 | Stock | 224<br>2961 |
| 332 | 8-9-37-26W4 | 3170 | 382 | 282 - 382 | Stock | 185<br>2985 |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.²) | $Q_{20}$ (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| 164<br>2946 | Bedrock | Sandstone<br>siltstone | 30 | 26,158<br>(K = 581) | 372 | |
| 97<br>2853 | Bedrock | Shale<br>siltstone | 100 + | 190<br>(K = 14.6) | 9 | Recovery data |
| 91<br>2914 | | | | | | Chem. analysis available |
| 35<br>2990 | Bedrock | Sandstone | 75 | 1010<br>(K = 25) | 36 | |
| 16<br>3009 | Bedrock | Sandstone<br>shale | ? | | | |
| 40<br>2960 | Bedrock | Sandstone | 30 + | 370<br>(K = 7) | 5 | Chem. analysis available |
| 30<br>2920 | Bedrock | Sandstone | 60 | 650<br>(K = 21.8) | 19 | |
| 8<br>2902 | Bedrock | Sandstone | 55 + | 290<br>(K = 13.3) | 8 | |
| 12<br>3148 | Bedrock | Siltstone<br>shale<br>sandstone | 65 | 40<br>(K = 3.4) | 1 | |
| | Bedrock | Siltstone<br>shale<br>sandstone | | | | Chem. analysis available |
| 90<br>3115 | Bedrock | Siltstone<br>shale | 45 | 280 | | Chem. analysis available |
| 10<br>3175 | Bedrock | Sandstone<br>siltstone | 45 | 660<br>(K = 20) | 14 | Pump test data |
| 23<br>3162 | Bedrock | Siltstone<br>shale<br>sandstone | 40 | 1330<br>(K = 16.3) | 25 | |
| 42<br>3128 | Bedrock | Sandstone<br>coals | 190 | 80<br>(K = 2) | 7 | |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| 333 | 8-9-37-26W4 | 3180 | 240 | 215 - 240 | Stock | 179<br>3001 |
| 334 | 5-10-37-26W4 | 3185 | 185 | 138 - 185 | Stock | 137<br>3048 |
| 335 | 13-10-37-26W4 | 3150 | 140 | 100 - 140 | Domestic | 100<br>3050 |
| 335.5 | NE-10-37-26W4 | 3180 | 90 | 70 - 90 | Stock | 41<br>3139 |
| 336 | NW-12-37-26W4 | 3240 | 82 | | | |
| 337 | SW-13-37-26W4 | 3200 | 125 | | | |
| 338 | 1-15-37-26W4 | 3165 | 105 | 90 - 105 | Domestic stock | 32<br>3133 |
| 339 | 3-15-37-26W4 | 3140 | 130 | 60 - 130 | Domestic stock | 95<br>3045 |
| 340 | 2-21-37-26W4 | 3060 | 84 | | Domestic stock | 40<br>3020 |
| 341 | 4-22-37-26W4 | 3057 | 45 | | Shothole | 0<br>3057 + |
| 342 | 15-22-37-26W4 | 3160 | 64 | 57 - 64 | Domestic stock | 15<br>3145 |
| 343 | 1-23-37-26W4 | 3435 | 262 | 183 - 262 | Domestic | 231<br>3204 |
| 344 | 1-24-37-26W4 | 3440 | 500 | | Abandoned | 187<br>3253 |
| 345 | 1-24-37-26W4 | 3440 | 210 | 200 - 210 | Domestic | 185<br>3255 |
| 346 | 1-24-37-26W4 | 3440 | 400 | | Domestic | 179<br>3261 |
| 347 | 12-24-37-26W4 | 3300 | 96 | | Stock | 46<br>3254 |
| 348 | 13-25-37-26W4 | 3150 | 80 | 50 - 80 | Domestic | 18<br>3112 |
| 349 | NE-25-37-26W4 | 3190 | 98 | | Domestic | 6<br>3184 |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.²) | $Q_{70}$ (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| 27<br>3153 | Bedrock | Sandstone | 55 | 820<br>(K = 41) | 21 | |
| 12<br>3173 | Bedrock | Fractured shale sandstone | 40 | 760<br>(K = 15) | 14 | Recovery data |
| 22<br>3138 | Bedrock | Siltstone sandstone | 35 | 700<br>(K = 12) | 12 | |
| 70<br>3120 | Bedrock | Shale Siltstone | 40 | 3860<br>(K = 97) | 73 | Pump test data |
| | | | | | | Chem. analysis available |
| | | | | | | Chem. analysis available |
| 85<br>3080 | Bedrock | Shale Siltstone | 65 | 560<br>(K = 16) | 17 | |
| 22<br>3118 | Bedrock | Sandstone | 30 | 13,080<br>(K = 654) | 186 | |
| 70<br>2990 | Bedrock | Sandstone | 40+ | | | |
| | | | | | | 0 - 45 clay |
| | | | | | | Chem analysis available |
| 40<br>3395 | Bedrock | Shale Sandstone | 30 | 980<br>(K = 38) | 2 | Pump test data |
| 43<br>3397 | Bedrock | Siltstone shale sandstone | 13 | 290<br>(K = 38) | 2 | |
| 43<br>3397 | Bedrock | Sandstone | 9 | 8890<br>(K = 444) | 38 | |
| | Bedrock | Sandstone siltstone | 20 | 500<br>(K = 23) | 5 | Pump test data |
| 18<br>3132 | Bedrock | Fractured shale siltstone | 25 | 2430<br>(K = 122) | 29 | |
| | | | | | | Chem. analysis available |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| 350 | 3-27-37-26W4 | 3125 | 33 | | | 12<br>3113 |
| 351 | 1-34-37-26W4 | 3079 | 60 | | Shothole | 0<br>3079 + |
| 352 | 8-34-37-26W4 | 3085 | 90 | | Stock | 32<br>3053 |
| 353 | 1-35-37-26W4 | 3105 | 150 | | Shothole | 0<br>3105 + |
| 354 | NE-35-37-26W4 | 2985 | 151 | 118 - 151 | Stock | 99<br>2886 |
| 355 | 8-36-37-26W4 | 3100 | 76 | 61 - 76 | Stock | 27<br>3073 |
| 356 | 8-36-37-26W4 | 3100 | 120 | 90 - 120 | Stock | 50<br>3050 |
| 357 | 8-36-37-26W4 | 3100 | 85 | | | 0<br>3100 + |
| 358 | 14-36-37-26W4 | 3030 | 140 | 58 - 140 | Domestic stock | 67<br>2963 |
| 359 | 14-36-37-26W4 | 3030 | 130 | 60 - 130 | Domestic stock | 75<br>2955 |
| L-1 | SE-14-35-25W4 | 3142 | 120 | | Domestic stock | |
| L-2 | NE-20-35-25W4 | 3145 | 145 | | Domestic stock | |
| L-3 | SW-28-35-25W4 | 3125 | 22 | Dug | Domestic stock | 18<br>3107 |
| L-4 | SE-30-35-25W4 | 3080 | 111 | | Domestic stock | 90<br>2990 |
| L-5 | SE-34-35-25W4 | 3090 | 136 | | Domestic stock | |
| L-6 | NW-34-35-25W4 | 3175 | 101 | | Domestic stock | 40<br>3135 |
| L-7 | SW-36-35-25W4 | 2945 | 0 | | Spring | 0<br>2945 + |
| L-8 | NW-4-36-25W4 | 3260 | 85 | | Domestic stock | |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.²) | Q (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| | Drift | | | | | |
| 65<br>3020 | Bedrock | Sandstone shale | 50 | 3667<br>(K = 122) | 87 | |
| 63<br>2922 | Bedrock | Sandstone | 45 | 500<br>(K = 39) | 11 | |
| 59<br>3041 | Bedrock | Fractured shale | 40 | 13,730<br>(K = 549) | 260 | |
| 87<br>3013 | Bedrock | Sandstone siltstone | 60 | 1635<br>(K = 41) | 47 | Chem. analysis available |
| 43<br>2987 | Bedrock | Siltstone shale sandstone | 40 | 1510<br>(K = 28) | 29 | |
| 42<br>2988 | Bedrock | Shale sandstone coal | 15 | 4670<br>(K = 104) | 33 | |
| 60<br>3082 | Bedrock | | | | | |
| 95<br>3050 | Bedrock | | | | | |
| | Drift | | | | | |
| 85<br>2995 | Bedrock | | | | | |
| | Bedrock | | | | | |
| | Bedrock | | | | | |
| | Drift | | | | | |
| | Bedrock | | | | | |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| L-9 | NE-11-36-25W4 | 2990 | 86 | | Domestic stock | 46<br>2944 |
| L-10 | SW-27-36-25W4 | 3032 | 14 | Dug | Domestic stock | 10<br>3022 |
| L-11 | SE-28-36-25W4 | 3045 | 35 | Dug | Domestic stock | 30<br>3015 |
| L-12 | SW-28-36-25W4 | 3090 | 180 | | Domestic stock | |
| L-13 | SW-30-36-25W4 | 3190 | 120 | | Domestic stock | 45<br>3145 |
| L-14 | NW-30-36-25W4 | 3190 | 60 | | Domestic stock | 50<br>3140 |
| L-15 | NE-12-36-26W4 | 3090 | 24 | Dug | Domestic stock | 23<br>3067 |
| L-16 | NW-13-36-26W4 | 3085 | 130 | | Domestic stock | |
| L-17 | NW-23-36-26W4 | 3150 | 120 | | Domestic stock | 10<br>3140 |
| L-18 | SW-25-36-26W4 | 3124 | 75 | | Domestic stock | 20<br>3104 |
| L-19 | NE-26-36-26W4 | 3105 | 60 | | Domestic stock | 4<br>3101 |
| L-20 | SE-36-36-26W4 | 3237 | 64 | | Domestic stock | 40<br>3197 |
| L-21 | NW-1-37-25W4 | 3122 | 20 | Dug | Domestic stock | <20 |
| L-22 | NE-3-37-25W4 | 3080 | 115 | | Domestic stock | 85<br>2995 |
| L-23 | SW-6-37-25W4 | 3153 | 36 | Dug | Domestic stock | +2<br>3155 |
| L-24 | SW-10-37-25W4 | 3065 | 100 | | Domestic stock | |
| L-25 | NW-23-37-25W4 | 3003 | 25 | Dug | Domestic stock | <25 |
| L-26 | SE-28-37-25W4 | 3033 | 108 | | Domestic stock | 78<br>2955 |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (igpd/ft.) and K (igpd/ft.²) | $Q_{20}$ (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| 40<br>2950 | Bedrock | | | | | |
| | Drift | | | | | |
| | Drift | | | | | |
| | Bedrock | | | | | |
| 100<br>3090 | Bedrock | | | | | |
| | Drift | | | | | |
| | Drift | | | | | |
| | Bedrock | | | | | |
| 50<br>3100 | Bedrock | | | | | |
| 60<br>3064 | Bedrock | | | | | |
| 60+ | Drift | Gravel | | | | |
| | Bedrock | | | | | |
| >70 | Drift | | | | | |
| 90<br>2990 | Bedrock | | | | | |
| | Drift | | | | | |
| 100<br>2965 | Drift | | | | | |
| >25 | Drift | | | | | |
| 91<br>2942 | Bedrock | | | | | |
| | Drift | | | | | |

| Index Number | Location | Elevation (map) In feet a.m.s.l. | Depth of Well (ft.) | Construction, Depth Interval Open to Aquifers (feet) | Use | Depth to Water Elev. (feet) |
|---|---|---|---|---|---|---|
| L-27 | SW-2-37-26W4 | 3152 | 0 | | Spring | 0<br>3152 + |
| L-28 | NE-10-37-26W4 | 3180 | 65 | | Domestic stock | 25<br>3155 |
| L-29 | NW-24-37-26W4 | 3339 | 74 | | Domestic stock | |
| L-30 | NE-26-37-26W4 | 3110 | 98 | | Domestic stock | 6<br>3104 |
| L-31 | SW-35-37-26W4 | 3072 | 100 | | Domestic stock | 25<br>3047 |

| Depth to Bedrock Elev. (feet) | Type of Well | Lithology of Aquifer | Available Drawdown (feet) | T (lgpd/ft.) and K (lgpd/ft.$^2$) | $Q_{20}$ (igpm) | Other Remarks |
|---|---|---|---|---|---|---|
| >65 | Drift | | | | | |
| 10<br>3329 | Bedrock | | | | | |
| 85<br>3025 | Bedrock | | | | | |
| | Bedrock | | | | | |

## APPENDIX B: Hydrochemical Analyses

Notes to Appendix B

1. Column 3: TDS = total dissolved solids as determined by weighing the residue on drying.
2. Columns 3 to 12: epm = equivalents per million, and the symbol % = percentage epm of the ion to the total respective cations or anions.
3. Columns 3 and 4: When the entry $Ca^{+} Mg^{=}$ is present, this indicates that these constituents were estimated from the reported "hardness" and not determined individually.
4. Columns 14 and 15: ppm = parts per million concentrations.
5. Column 16: Facies type refers to the classification (figures 41 and 42) given in the text.

| Index Number | Well Depth Date Sampled (feet) | TDS ppm | Na | | K | | Ca | | Mg | | Na + K | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | epm | % | epm | % | epm | % | epm | % | epm | % |
| 2 | 75<br>13-12-76 | 1071 | 12.53 | 65.8 | 0.09 | 0.47 | 3.14 | 16.5 | 3.29 | 17.3 | 12.62 | 66.3 |
| 4 | 108<br>17-2-60 | 736 | | | | | 10.58 | Ca + | Mg = 97.0 | | 0.32 | 3 |
| 5 | 190<br>21-6-77 | 2145 | 22.23 | 61.2 | 0.10 | 0.3 | 7.24 | 20.0 | 6.58 | 18.1 | 22.33 | 61.5 |
| 9 | 252<br>10-8-60 | 1026 | | | | | 8.98 | Ca + | Mg = 65.6 | | 4.71 | 34.4 |
| 12 | 300<br>2-6-64 | 782 | | | | | 0.2 | Ca + | Mg = 1.4 | | 13.85 | 98.6 |
| 13 | 230<br>12-4-61 | 1510 | | | | | 10.58 | Ca + | Mg = 49.4 | | 10.66 | 49.8 |
| 14 | 215<br>8-1-68 | 1676 | 7.39 | 60.8 | | | 4.77 | Ca + | Mg = 39.2 | | | |
| 16 | 266<br>7-5-74 | 1229 | 5.61 | 26.9 | 0.4 | 0.2 | 8.48 | 40.6 | 6.74 | 32.3 | 5.65 | 27.0 |
| 18 | 118<br>26-6-73 | 1090 | 11.31 | 76.1 | 0.6 | 0.4 | 1.85 | 12.4 | 1.65 | 11.1 | 11.37 | 76.5 |
| 19 | 90<br>3-9-72 | 517 | 1.05 | 10.8 | 0.10 | 1.0 | 4.59 | 47.0 | 4.03 | 41.3 | 1.15 | 11.8 |
| 22 | 80<br>19-5-77 | 642 | 2.92 | 26.5 | 0.11 | 1.0 | 3.49 | 31.7 | 4.44 | 40.3 | 3.03 | 27.5 |
| 25 | 58<br>20-10-65 | 844 | | | | | 4.19 | Ca + | Mg = 30.0 | | 9.77 | 70.0 |
| 26 | 132<br>30-8-68 | 886 | 12.18 | 76.7 | | | 3.57 | Ca + | Mg = 2.25 | | | |
| 33 | 158<br>7-10-69 | 1130 | | | | | 5.21 | Ca + | Mg = 67 | | 7.53 | 33 |
| 34 | 81<br>18-8-72 | 1380 | | | | | 1.35 | 6.74 | 2.14 | 10.7 | 16.53 | 83 |
| 37 | 110<br>31-3-61 | 1178 | | | | | 4.59 | Ca + | Mg = 24 | | 14.60 | 76 |
| 38 | 50<br>15-9-77 | 544 | 1.13 | 11.6 | .10 | 1.0 | 4.39 | 45.1 | 4.11 | 42.2 | 1.23 | 12.6 |
| 40 | 96<br>7-1-68 | 1332 | 14.53 | 89.5 | | | 1.7 | Ca + | Mg = 10.5 | | | |
| 41 | 80<br>7-1-68 | 886 | 18.5 | 98.5 | | | .28 | Ca + | Mg = 1.5 | | | |

| Ca/Mg ratio | Cl epm | Cl % | $SO_4$ epm | $SO_4$ % | $HCO_3 + CO_3$ epm | $HCO_3 + CO_3$ % | $NO_3$ epm | $NO_3$ % | Fe ppm | F ppm | Facies Type |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.95 | 0.06 | 0.3 | 6.83 | 37.0 | 11.57 | 62.7 | Tr. | | 0.28 | 0.43 | 1 |
| | | | 2.52 | 23.1 | 8.26 | 75.8 | 0.12 | 1.1 | | | 2 |
| 1.10 | 0.09 | 0.3 | 21.28 | 62.5 | 12.65 | 37.1 | Tr. | | 4.71 | 0.92 | 3 |
| | 0.11 | 0.8 | 6.79 | 49.6 | 6.79 | 49.6 | | | 0.4 | | 4 |
| | 0.62 | 4.4 | 0.15 | 1.1 | 13.28 | 94.5 | | | | | 1 |
| | 0.06 | 0.1 | 11.03 | 51.5 | 10.33 | 48.2 | | | 5.0 | 0.20 | 4 |
| | 0.17 | 0.7 | 16.66 | 64.6 | 8.95 | 14.7 | 0.05 | 0.1 | 0.10 | 0.66 | 3 |
| 1.26 | 0.11 | 0.5 | 11.9 | 57.0 | 8.87 | 42.5 | Tr. | | 0.50 | 0.48 | 4 |
| 1.12 | 0.03 | 0.2 | 2.23 | 17.0 | 10.83 | 82.7 | Tr. | | Tr. | | 1 |
| 1.14 | 0.05 | 0.50 | 1.66 | 16.8 | 8.14 | 82.5 | 0.11 | 1.1 | | 0.15 | 2 |
| 0.79 | 0.06 | 0.50 | 1.48 | 27.9 | 8.62 | 69.1 | 0.32 | 2.6 | 0.07 | 0.12 | 2 |
| | | | 3.73 | 26.7 | 10.23 | 73.3 | | | | | 1 |
| | .06 | 0.41 | 4.13 | 28.1 | 10.52 | 71.5 | | | 3.52 | | 1 |
| | .11 | 0.5 | 7.85 | 34.5 | 13.47 | 59.2 | | | 36.5 | | 4 |
| 0.63 | 0.9 | 0.5 | 9.27 | 46.3 | 10.66 | 53.2 | Tr. | | 0.2 | | 3 |
| | .06 | 0.3 | 8.06 | 42.1 | 11.07 | 57.9 | | | 2.23 | | 3 |
| 1.07 | .31 | 3.1 | 2.48 | 24.9 | 6.11 | 61.5 | 1.04 | 10.5 | 0.16 | 0.11 | 2 |
| | .06 | 0.3 | 9.02 | 47.1 | 10.03 | 52.4 | .03 | 0.2 | 0.03 | 0.76 | 3 |
| | .11 | 0.75 | 3.58 | 24.5 | 10.92 | 74.7 | | | 0.27 | 1.27 | 1 |

| Index Number | Well Depth Date Sampled (feet) | TDS ppm | Na | | K | | Ca | | Mg | | Na + K | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | epm | % | epm | % | epm | % | epm | % | epm | % |
| 46 | 215<br>7-1-68 | 702 | | | | | 7.37 | Ca + | Mg = 65.2 | | 3.93 | 34.8 |
| 48 | SPRING<br>31-1-61 | 1280 | | | | | 11.88 | Ca + | Mg = 63 | | 6.88 | 37 |
| 52 | 115<br>2-3-77 | 1743 | 25.8 | 93.7 | 25 | 0.9 | 1.15 | 4.2 | .33 | 1.2 | 26.05 | 94.6 |
| 54 | 150<br>26-8-74 | 633 | 7.74 | 67.8 | .07 | 0.6 | 1.3 | 11.4 | 2.3 | 20.2 | 7.81 | 68.5 |
| 58 | 290<br>21-4-60 | 748 | | | | | | | | | | |
| 59 | 102<br>16-8-72 | 428 | | | | | 1.60 | 25.9 | | 7.9 | 4.09 | 92.1 |
| 60 | 60<br>5-4-77 | 204 | 1.61 | 35.1 | .097 | 2.1 | 1.15 | 25.1 | 1.73 | 37.7 | 1.71 | 37.2 |
| 61 | 125<br>30-10-75 | 710 | 14.14 | 99.5 | .064 | 0.5 | 0.05 | | 0.08 | | 14.2 | 100.0 |
| 66 | 130<br>21-9-75 | 893 | 12.44 | 95.8 | .008 | 0.06 | 0.45 | 3.5 | 0.08 | 0.62 | 12.45 | 95.9 |
| 67 | 120<br>18-11-75 | 1585 | 21.49 | 92.4 | .05 | 0.2 | 1.30 | 5.6 | 0.41 | 1.8 | 21.54 | 92.7 |
| 68 | 132<br>18-9-60 | 1356 | | | | | 3.0 | Ca + | Mg = 14.0 | | 18.32 | 86.0 |
| 69 | 183<br>-7-70 | 804 | | | | | 1.76 | Ca + | Mg = 14.0 | | 11.03 | 86.0 |
| 84 | 257<br>-5-68 | 792 | | | | | 0.28 | Ca + | Mg = 2.1 | | 12.91 | 97.0 |
| 88 | 65<br>23-8-76 | 366 | 0.87 | 13.0 | .08 | 1.2 | 4.89 | 73.3 | 0.82 | 12.3 | .95 | 14.2 |
| 90 | 62<br>-8-71 | 920 | | | | | 0.35 | 2.2 | 1.65 | 10.6 | 13.64 | 87.0 |
| 92 | 90<br>20-9-76 | 373 | 1.39 | 18.8 | .09 | 1.2 | 3.09 | 41.8 | 2.8 | 37.9 | 1.48 | 20.0 |
| 94 | 71<br>2-6-74 | 306 | .48 | 7.7 | .067 | 1.1 | 2.5 | 39.9 | 3.21 | 51.3 | .55 | 8.8 |
| 99 | <br>-6-68 | 526 | | | | | 2.36 | Ca + | Mg = 25.0 | | 7.0 | 75.0 |
| 100 | 60 | 344 | | | | | 3.81 | Ca + | Mg = 69.0 | | 1.73 | 31.0 |

| Ca/Mg ratio | Cl epm | % | $SO_4$ epm | % | $HCO_3 + CO_3$ epm | % | $NO_3$ epm | % | Fe ppm | F ppm | Facies Type |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | .06 | 0.53 | 2.98 | 26.4 | 8.26 | 73.1 | | | 0.40 | 0.23 | 2 |
| | .09 | 0.5 | 8.25 | 41.0 | 10.42 | 55.5 | Tr | | 0.80 | | 4 |
| 3.49 | .14 | 0.5 | 15.57 | 56.2 | 11.98 | 43.3 | Tr. | | 0.12 | 0.47 | 3 |
| 0.57 | .11 | 0.97 | 2.94 | 25.9 | 8.31 | 73.2 | Tr | | Tr. | 0.19 | 1 |
| | | | 2.58 | 22 | 9.44 | 78 | | | 0.30 | | |
| 3.27 | 0.03 | 0.5 | 1.06 | 17.2 | 5.08 | 82.3 | 0.01 | | | 0.1 | 1 |
| 0.67 | 0.11 | 2.9 | 0.2 | 5.2 | 3.51 | 91.9 | Tr. | | 3.44 | 0.12 | 2 |
| | Tr. | | 0.81 | 7.0 | 10.7 | 92.7 | Tr. | | 0.80 | 0.47 | 1 |
| | 0.40 | 2.5 | 6.20 | 38.4 | 9.51 | 58.9 | 0.02 | 0.10 | 0.10 | 0.91 | 3 |
| 3.17 | .03 | 0.1 | 14.8 | 56.1 | 11.54 | 43.8 | Tr. | | 0.10 | 0.93 | 3 |
| | .17 | 0.8 | 9.91 | 46.5 | 11.24 | 52.7 | | | 0.12 | | 3 |
| | .06 | 0.5 | 4.62 | 36.1 | 8.06 | 63.0 | Tr | | 0.40 | | 1 |
| | .06 | 0.5 | 3.03 | 22.9 | 10.13 | 76.2 | | | 3.18 | 1.23 | 1 |
| 5.96 | Tr. | | 0.67 | 9.0 | 5.75 | 90.9 | Tr. | | 0.40 | 0.13 | 2 |
| 0.21 | .09 | 0.6 | 5.21 | 33.3 | 10.33 | 66.1 | .008 | .05 | | | 1 |
| 1.10 | .03 | 0.37 | .21 | 2.6 | 7.98 | 97.1 | Tr. | | 0.60 | 0.13 | 2 |
| 0.78 | .23 | 3.7 | .58 | 9.3 | 5.43 | 86.9 | Tr. | | 0.20 | 0.20 | 2 |
| | 0.11 | 1.2 | 2.12 | 22.7 | 7.12 | 76.2 | | | 0.6 | | 1 |
| | 0.11 | 2.0 | 0.42 | 7.6 | 5.00 | 90.3 | | | 1.01 | 0.16 | 2 |

| Index Number | Well Depth Date Sampled (feet) | TDS ppm | Na | | K | | Ca | | Mg | | Na + K | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | epm | % | epm | % | epm | % | epm | % | epm | % |
| 103 | -6-68<br>140<br>28-5-76 | 867 | 13.31 | 96.4 | 0.02 | .15 | 0.4 | 2.9 | 0.08 | .6 | 13.33 | 96.6 |
| 106 | 100<br>-5-68 | 874 | | | | | 3.11 | Ca + | Mg = 22.0 | | 10.76 | 78.0 |
| 109 | 108<br>8-6-77 | 360 | 2.83 | 41.0 | 0.08 | 1.2 | 1.70 | 24.6 | 2.30 | 33.3 | 2.91 | 42.2 |
| 113 | 47<br>-5-61 | 1224 | 13.31 | 81.7 | | | 2.99 | Ca + | Mg = 18.3 | | | |
| 122 | 90<br>-9-59 | 396 | | | | | 5.79 | Ca + | Mg = 90.0 | | 0.67 | 10.0 |
| 123 | 165<br>-5-68 | 840 | 14.35 | 99.5 | | | 0.08 | Ca + | Mg = 0.5 | | 0.17 | 1.3 |
| 125 | 90<br>-5-68 | 546 | | | | | 7.58 | Ca + | Mg = 29.0 | | 6.39 | 71.0 |
| 129 | 130<br>-9-68 | 828 | | | | | 8.60 | Ca + | Mg = 53.0 | | 7.7 | 47.0 |
| 137 | 140<br>-5-68 | 1528 | 22.75 | 98.9 | | | 0.26 | Ca + | Mg = 1.1 | | | |
| 139 | 200 | 816 | 14.72 | 97.4 | | | 0.40 | Ca + | Mg = 2.6 | | | |
| 148 | 200<br>-5-68 | 1784 | | | | | 0.62 | Ca + | Mg = 2.4 | | 25.64 | 97.6 |
| 155 | 123<br>-8-62 | 986 | | | | | 3.71 | Ca + | Mg = 23.3 | | 12.22 | 76.7 |
| 156 | 74<br>20-4-60 | 874 | | | | | 5.79 | Ca + | Mg = 40.1 | | 8.58 | 59.5 |
| 170 | 92<br>29-5-77 | 884 | 14.66 | 97.6 | 0.03 | 0.2 | 0.25 | 1.7 | 0.08 | 0.05 | 14.69 | 97.8 |
| 171 | 110<br>21-5-73 | 1088 | 9.79 | 76.8 | 0.069 | 0.54 | 2.30 | 18.1 | 0.49 | 3.85 | 9.86 | 77.4 |
| 172 | 71<br>23-7-70 | 1020 | | | | | 2.30 | Ca + | Mg = 13.9 | | 14.17 | 85.8 |
| 173 | 50<br>6-6-74 | 1046 | 13.75 | 78.2 | 0.09 | 0.5 | 1.75 | 9.95 | 1.97 | 11.2 | 13.84 | 78.7 |
| 176 | 155<br>9-8-76 | 687 | 14.83 | 97.3 | 0.03 | 0.2 | 0.30 | 1.97 | 0.08 | 0.5 | 14.86 | 97.5 |
| 178 | 100<br>15-5-77 | 375 | 1.00 | 12.3 | 0.07 | 0.9 | 3.64 | 44.9 | 3.37 | 41.6 | 1.07 | 13.2 |

| Ca/Mg ratio | Cl epm | % | $SO_4$ epm | % | $HCO_3$ + $CO_3$ epm | % | NO epm | % | Fe ppm | F ppm | Facies Type |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.03 | 0.2 | 5.81 | 38.9 | 9.10 | 60.9 | Tr. | | 0.30 | 1.30 | 1 |
| | 0.06 | 0.4 | 4.96 | 35.8 | 8.85 | 63.8 | | | 0.77 | 0.16 | 1 |
| 0.74 | 0.14 | 2.0 | 0.67 | 9.3 | 6.38 | 88.7 | Tr. | | 0.28 | 0.08 | 2 |
| | 0.11 | 0.6 | 7.5 | 40.7 | 10.62 | 57.7 | | | | | 3 |
| | | | | | 6.46 | 99.0 | .021 | | 0.40 | | 1 |
| | 0.17 | 1.3 | 4.64 | 35.2 | 8.36 | 63.5 | | | | 1.00 | 1 |
| | 0.40 | 4.5 | 2.46 | 27.4 | 6.10 | 68.0 | .01 | 0.1 | 0.06 | 0.16 | 1 |
| | 0.17 | 1.0 | 5.21 | 32.0 | 10.42 | 63.9 | | | 14.0 | | 2 |
| | 0.06 | 0.3 | 10.56 | 44.0 | 13.37 | 55.7 | | | 0.06 | 0.66 | 3 |
| | 0.06 | 0.9 | 3.91 | 56.5 | 2.95 | 42.6 | | | 0.60 | | 3 |
| | 0.06 | 0.2 | 14.10 | 53.7 | 12.10 | 46.1 | | | 0.02 | 0.90 | 3 |
| | 0.11 | 0.7 | 6.06 | 38.0 | 9.74 | 61.1 | | | 1.15 | 0.45 | 1 |
| | | | 3.91 | | 10.52 | | | | 1.7 | | 2 |
| 3.13 | 0.03 | | 4.56 | 29.8 | 10.72 | 70.0 | Tr. | | 0.08 | 0.68 | 1 |
| 4.69 | 0.09 | 0.6 | 3.75 | 26.7 | 10.18 | 72.6 | Tr. | | 2.4 | 0.23 | 1 |
| | 0.06 | 0.4 | 5.50 | 33.3 | 10.96 | 66.3 | | | 1.36 | | 1 |
| 0.89 | .11 | 0.6 | 6.25 | 34.2 | 11.90 | 65.1 | Tr. | | 0.70 | 0.52 | 1 |
| 3.75 | 0.09 | 0.8 | 0.21 | 1.9 | 10.80 | 96.7 | Tr. | | Tr | 1.15 | 1 |
| 1.08 | 0.14 | 1.9 | 0.65 | 8.7 | 6.69 | 89.4 | Tr. | | 0.58 | 0.08 | 2 |

| Index Number | Well Depth Date Sampled (feet) | TDS ppm | Na | | K | | Ca | | Mg | | Na + K | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | epm | % | epm | % | epm | % | epm | % | epm | % |
| 180 | 93<br>27-7-75 | 540 | 7.92 | 81.4 | 0.05 | 0.5 | 1.25 | 12.9 | 0.49 | 5.0 | 7.97 | 81.9 |
| 181 | 98<br>10-9-73 | 513 | 8.7 | 94.7 | 0.21 | 2.3 | 0.20 | 2.2 | 0.08 | 0.9 | 8.91 | 97.0 |
| 185 | 100<br>18-12-61 | 916 | | | | | 3.29 | Ca+ | Mg = 26.1 | | 9.29 | 73.9 |
| 188 | 180<br>8-1-68 | 892 | 18.17 | 98.9 | | | 0.20 | Ca+ | Mg = 1.1 | | | 98.9 |
| 189 | 185<br>-4-64 | 1802 | | | | | 15.77 | Ca+ | Mg = 68.5 | | 7.09 | 30.8 |
| 194 | 105<br>-70 | 790 | 17.07 | 97.5 | | | 0.42 | Ca+ | Mg = 2.4 | | | 97.5 |
| 195 | 122<br>-2-61 | 666 | 14.66 | 96.7 | | | 0.50 | Ca+ | Mg = 3.3 | | | |
| 196 | 190<br>-8-75 | 611 | 10.75 | 98.4 | 0.015 | 0.14 | 0.05 | 0.5 | 0.08 | 0.7 | 10.77 | 98.5 |
| 197 | 95<br>11-8-71 | 510 | | | | | 1.35 | 18.2 | 2.88 | 38.8 | 3.2 | 43.1 |
| 198 | 94<br>30-6-65 | 494 | | | | | 6.49 | Ca+ | Mg = 81.8 | | 1.44 | 18.2 |
| 199 | 190<br>2-8-77 | 818 | 13.40 | 88.9 | 0.077 | 0.5 | 1.0 | 6.6 | 0.58 | 3.9 | 13.48 | 89.4 |
| 200 | 165<br>-2-61 | 520 | | | | | 4.99 | Ca+ | Mg = 55.0 | | 4.10 | 45.0 |
| 201 | 83 | 9.15 | | | | | 0.30 | 2.1 | 0.41 | 2.9 | 13.31 | 94.7 |
| 203 | 60<br>-9-75 | 539 | 9.05 | 96.5 | 0.02 | 0.21 | 0.20 | 2.1 | 0.08 | 0.9 | 9.07 | 96.7 |
| 204 | 100<br>14-2-75 | 528 | 9.09 | 93.1 | 0.03 | 0.31 | 0.55 | 5.6 | 0.082 | 0.8 | 9.12 | 93.4 |
| 205 | 90<br>27-7-76 | 619 | 8.18 | 80.8 | 0.06 | 0.6 | 0.65 | 6.4 | 1.23 | 12.1 | 8.24 | 81.3 |
| 209 | 105<br>-6-75 | 856 | 14.40 | 97.5 | 0.02 | 0.14 | 0.25 | 1.7 | 0.082 | 0.56 | 14.42 | 97.6 |
| 211 | 80<br>28-7-75 | 910 | 16.01 | 97.7 | 0.03 | 0.18 | 0.25 | 1.5 | 0.082 | 0.5 | 16.04 | 97.9 |
| 216 | 122<br>-8-65 | 750 | | | | | 2.79 | Ca+ | Mg = 22.4 | | 9.49 | 76.2 |

| Ca/Mg ratio | Cl epm | % | $SO_4$ epm | % | $HCO_3 + CO_3$ epm | % | $NO_3$ epm | % | Fe ppm | F ppm | Facies Type |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2.55 | 0.06 | 0.6 | 0.29 | 2.8 | 10.08 | 96.2 | Tr. | | 0.60 | 1.01 | 1 |
| 2.5 | 0.028 | 0.3 | 1.21 | 13.4 | 7.75 | 86.0 | Tr. | | 0.10 | 0.50 | 1 |
| | 0.028 | 0.2 | 8.20 | 65.2 | 4.33 | 34.4 | Tr. | | 0.20 | 0.34 | 3 |
| | 0.06 | 0.4 | 4.02 | 27.2 | 10.64 | 72.0 | | | 0.08 | 1.11 | 1 |
| | | | 13.39 | | 9.64 | | | | 4.80 | | 4 |
| | 0.06 | 0.5 | 2.46 | 19.3 | 10.23 | 80.2 | | | 0.24 | | 1 |
| | Tr. | | 1.94 | 17.8 | 8.95 | 82.2 | | | 0.20 | | 1 |
| | 0.20 | 1.7 | 1.00 | 8.4 | 10.25 | 86.1 | Tr. | | 0.90 | 8.75 | 1 |
| 0.47 | 0.09 | 1.2 | 0.63 | 8.5 | 6.69 | 90.0 | 0.0 | 0.2 | | | 2 |
| | | 0.98 | | 126.88 .4 | | 860.07 .8 | | 0. 9 | Tr. | | 2 |
| 1.72 | 3.86 | 24.8 | 0.21 | 1.4 | 11.43 | 73.6 | Tr. | | 0.76 | 0.68 | 1 |
| | 0.06 | 0.7 | 0.90 | 9.9 | 8.16 | 89.5 | | | 0.80 | | 2 |
| 0.73 | 0.06 | 0.4 | 4.16 | 29.6 | 9.83 | 70.0 | Tr. | | 0.90 | | 1 |
| 2.5 | 0.14 | 1.5 | 2.35 | 25.2 | 6.68 | 71.6 | Tr. | | 0.90 | 3.00 | 1 |
| 6.71 | 0.028 | 0.3 | 1.58 | 17.5 | 7.41 | 81.9 | Tr. | | 0.30 | 0.51 | 1 |
| 0.53 | 0.06 | 0.5 | 2.50 | 21.1 | 9.27 | 78.1 | Tr. | | 0.40 | 0.74 | 1 |
| 3.05 | 0.14 | 1.0 | 5.95 | 43.9 | 7.38 | 54.5 | Tr. | | 0.40 | 1.23 | 3 |
| 3.05 | 0.028 | 0.2 | 4.62 | 30.8 | 10.3 | 68.6 | Tr. | | 0.60 | 1.22 | 1 |
| | | | 1.62 | 13.0 | 10.82 | 86.8 | 0.01 | 0.13 | 5.0 | | 1 |

| Index Number | Well Depth Date Sampled (feet) | TDS ppm | Na | | K | | Ca | | Mg | | Na + K | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | epm | % | epm | % | epm | % | epm | % | epm | % |
| 249 | 121 -5-68 | 432 | | | | | 2.93 | Ca + | Mg = 44.8 | | 3.11 | 47.6 |
| 269 | 130 -8-68 | 894 | | | | | 4.71 | Ca + | Mg = 33.8 | | 9.24 | 66.2 |
| 280 | 125 -3-59 | 1692 | | | | | 11.88 | Ca + | Mg = 48.3 | | 12.70 | 51.7 |
| 286 | 70 -12-73 | 1534 | 23.45 | 93.5 | 0.05 | 0.2 | 1.05 | 4.2 | 0.41 | 1.6 | | |
| 287 | 180 -68 | 1906 | | | | | 0.50 | Ca + | Mg = 1.7 | | 29.23 | 98.3 |
| 311 | 100 7-4-76 | 959 | 13.62 | 76.8 | 0.05 | 0.28 | 3.29 | 18.6 | 0.74 | 4.2 | 13.67 | 77.1 |
| 313 | 110 -68 | 2090 | | | | | 0.92 | Ca + | Mg = 3.0 | | 29.71 | 97.0 |
| 3.18 | 100 | 1360 | | | | | 1.35 | 6.3 | 1.23 | 5.7 | 18.93 | 87.8 |
| 322 | 150 -74 | 1544 | 24.45 | 96.0 | 0.23 | 0.9 | 0.70 | 2.8 | 0.08 | 0.3 | 24.68 | 96.9 |
| 327 | 50 7-6-65 | 704 | | | | | 0.30 | 2.5 | 0.17 | 1.4 | 11.64 | 96.1 |
| 329 | 140 15-4-77 | 766 | 13.57 | 95.4 | 0.036 | 0.25 | 0.45 | 3.2 | 0.17 | 1.2 | 13.61 | 95.6 |
| 336 | 82 21-4-78 | 729 | 12.18 | 98.3 | 0.023 | 0.19 | 0.10 | 0.81 | 0.082 | 0.66 | 12.20 | 98.5 |
| 337 | 125 -6-70 | 1010 | | | | | 0.60 | Ca + | Mg = 3.7 | | 15.5 | 96.3 |
| 342 | 64 12-10-65 | 440 | | | | | 1.05 | 14.1 | 3.54 | 47.6 | 2.75 | 37.1 |
| 349 | 98 3-6-68 | 1026 | 19.64 | 98.1 | | | 0.36 | Ca + | Mg = 1.8 | | | 98.1 |
| 356 | 120 -5-74 | 922 | 12.53 | 75.9 | 0.02 | 0.12 | 3.89 | 23.6 | 0.082 | 0.5 | 12.55 | 76.0 |
| 1-2 | 27-7-78 | 419 | 1.14 | 13.8 | 0.13 | 1.5 | 4.29 | 51.8 | 2.72 | 32.8 | 1.27 | 15.3 |
| 2-10 | 150 28-7-78 | 1355 | 3.18 | 13.0 | 0.10 | 0.4 | 6.09 | 24.9 | 15.06 | 61.7 | 3.28 | 13.4 |
| 2-11 | POUND 28-7-78 | 453 | 1.52 | 18.2 | 0.66 | 7.9 | 3.04 | 36.4 | 3.13 | 37.4 | 2.18 | 26.1 |
| 3-1A | SPRING 29-7-78 | 967 | 12.22 | 69.6 | 0.05 | 0.3 | 2.4 | 13.6 | 2.88 | 16.4 | 12.27 | 69.9 |

| Ca/Mg ratio | Cl | | $SO_4$ | | $HCO_3$ + $CO_3$ | | $NO_3$ | | Fe | F | Facies Type |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | epm | % | epm | % | epm | % | epm | % | ppm | ppm | |
| | 0.11 | 1.7 | 2.67 | 40.8 | 3.74 | 57.2 | 0.00 | 0.09 | 13.95 | 0.20 | 4 |
| | 0.11 | 0.8 | 4.77 | 34.2 | 8.93 | 64.0 | | | | 2.70 | 1 |
| | 0.09 | 0.4 | 13.26 | 53.9 | 11.21 | 45.6 | 0.01 | 0.06 | 0.20 | 0.20 | 4 |
| 2.56 | 0.028 | | 11.45 | | 13.34 | | 0.01 | | 3.60 | 0.31 | 3 |
| | 0.06 | 0.2 | 15.37 | 51.7 | 14.26 | 48.0 | | | 0.18 | 0.78 | 3 |
| 4.45 | 0.028 | 0.2 | 5.46 | 34.7 | 10.26 | 65.1 | Tr. | | 0.90 | 0.15 | 1 |
| | 0.11 | 0.36 | 16.45 | 53.7 | 14.05 | 45.9 | | | 0.38 | 0.55 | 3 |
| 1.10 | 0.17 | 0.79 | 9.89 | 45.9 | 11.51 | 53.4 | | | 1.60 | | 3 |
| 8.50 | 0.25 | 1.0 | 12.03 | 48.9 | 12.15 | 49.4 | 0.00 | | 0.50 | 0.96 | 3 |
| 1.77 | 0.23 | 1.9 | 1.98 | 16.4 | 9.83 | 81.2 | | | 0.10 | 1.30 | 1 |
| 2.65 | 0.09 | 0.7 | 2.12 | 15.8 | 11.12 | 83.0 | 0.02 | 0.15 | 0.30 | 1.00 | 1 |
| 1.22 | 0.056 | 0.4 | 2.79 | 21.2 | 10.29 | 78.1 | Tr. | | Tr. | 0.63 | 1 |
| | 0.11 | 0.7 | 4.31 | 26.8 | 11.68 | 72.6 | | | 0.06 | | 1 |
| 0.30 | 0.45 | 6.1 | 1.12 | 15.1 | 5.82 | 78.3 | | | 2.40 | 0.80 | 2 |
| | 0.056 | 0.33 | 5.04 | 30.0 | 11.67 | 69.4 | | | 0.55 | 0.93 | 1 |
| | 0.03 | 0.2 | 3.75 | 23.3 | 12.29 | 76.2 | Tr. | | Tr. | 0.88 | 1 |
| 1.58 | 0.11 | 1.4 | 0.67 | 8.1 | 7.44 | 90.3 | 0.02 | 0.3 | 0.10 | | 2 |
| 0.40 | 0.34 | 1.4 | 13.33 | 55.5 | 10.24 | 42.7 | 0.09 | 0.4 | 0.30 | 0.20 | 4 |
| 0.97 | 0.11 | 1.5 | 3.12 | 41.1 | 4.28 | 56.3 | 0.09 | 1.2 | 0.70 | 0.40 | 4 |
| 0.83 | 0.11 | 0.7 | 5.21 | 31.5 | 11.19 | 67.7 | 0.02 | 0.1 | 0.70 | 0.40 | 1 |

| Index Number | Well Depth Date Sampled (feet) | TDS ppm | Na | | K | | Ca | | Mg | | Na + K | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | epm | % | epm | % | epm | % | epm | % | epm | % |
| 3-18 | CREEK 29-7-78 | 494 | 5.48 | 60.7 | 0.18 | 2.0 | 1.15 | 12.7 | 2.22 | 24.6 | 5.66 | 62.7 |
| 3-7 | CREEK 29-7-78 | 476 | 5.57 | 60.7 | 0.18 | 2.0 | 1.20 | 13.1 | 2.22 | 24.2 | 5.75 | 62.7 |
| 4-1 | 266 1-8-78 | 1357 | 10.79 | 45.2 | 0.20 | 0.9 | 5.74 | 24.0 | 7.16 | 30.0 | 10.99 | 46.1 |
| 4-3 | SPRING 1-8-78 | 852 | 14.57 | 84.1 | | | 1.2 | 6.9 | 1.55 | 8.9 | 14.57 | 84.1 |
| 5-1A | 250 2-8-78 | 586 | 4.61 | 35.4 | 0.10 | 0.8 | 3.29 | 25.3 | 5.02 | 38.6 | 4.71 | 36.2 |
| 5-1B | SPRING 2-8-78 | 490 | 5.18 | 42.4 | 0.10 | 0.0 | 3.39 | 27.8 | 3.54 | 29.0 | 5.28 | 43.2 |
| 5-2 | SPRING 2-8-78 | 454 | 2.83 | 23.8 | 0.10 | 0.9 | 3.69 | 31.1 | 5.27 | 44.3 | 2.93 | 24.7 |
| 5-3A | 160 2-8-78 | 644 | 11.79 | 97.7 | 0.20 | 1.7 | 0.07 | 0.6 | | | 11.90 | 99.4 |
| 5-38 | POND 2-8-78 | 2446 | 28.27 | 70.8 | 0.87 | 2.2 | 0.52 | 1.3 | 10.29 | 25.7 | 29.14 | 73.0 |
| 5-5 | 58 2-8-78 | 769 | 9.83 | 69.3 | 0.15 | 1.1 | 2.15 | 15.1 | 2.06 | 14.5 | 9.98 | 70.4 |
| 5-6 | SPRING 2-8-78 | 876 | 11.05 | 71.1 | 0.10 | 0.7 | 1.85 | 11.9 | 2.55 | 16.4 | 11.15 | 71.8 |
| 6-1 | 70 3-8-78 | 831 | 2.78 | 17.6 | 0.61 | 3.9 | 5.74 | 36.3 | 6.67 | 42.2 | 33.9 | 21.5 |
| 6-2 | SPRING 3-8-78 | 642 | 4.48 | 34.9 | 0.06 | 0.5 | 4.19 | 32.6 | 4.12 | 32.0 | 4.53 | 35.4 |
| 6-3 | SLOUGH 3-8-78 | 830 | 6.66 | 42.2 | 1.46 | 9.2 | 1.90 | 12.0 | 5.76 | 36.5 | 8.12 | 51.4 |
| 6-4 | 15 3-8-78 | 1030 | 13.27 | 74.1 | 0.05 | 0.3 | 2.20 | 12.3 | 2.39 | 13.3 | 13.32 | 74.4 |
| 6-5 | 132 3-8-78 | 1177 | 17.79 | 86.2 | 0.03 | 0.15 | 1.39 | 6.7 | 1.42 | 6.9 | 17.82 | 86.35 |
| 6-6 | 220 3-8-78 | 716 | 12.79 | 99.4 | | 0.0 | 0.07 | 0.5 | | | 12.86 | 99.4 |
| 6-7 | SPRING 3-8-78 | 1080 | 15.92 | 86.7 | 0.05 | 0.3 | 1.03 | 5.6 | 1.36 | 7.40 | 15.97 | 87.0 |
| 6-8 | SPRING 3-8-78 | 1241 | 15.35 | 73.0 | 0.08 | 0.4 | 2.54 | 12.1 | 3.05 | 14.5 | 15.43 | 73.4 |

| Ca/Mg ratio | Cl epm | Cl % | $SO_4$ epm | $SO_4$ % | $HCO_3$ + $CO_3$ epm | $HCO_3$ + $CO_3$ % | $NO_3$ epm | $NO_3$ % | Fe ppm | F ppm | Facies Type |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.52 | 0.17 | 1.9 | 1.25 | 14.2 | 7.33 | 83.4 | 0.04 | 0.4 | 0.20 | 0.40 | 1 |
| 0.54 | 0.11 | 1.3 | 1.25 | 14.4 | 7.27 | 83.7 | 0.05 | 0.6 | 0.30 | 0.40 | 1 |
| 0.80 | 0.23 | 1.0 | 11.76 | 52.2 | 10.52 | 46.7 | 0.01 | 0.0 | 0.40 | | 4 |
| 0.78 | Tr. | | 4.37 | 27.1 | 11.72 | 72.6 | 0.06 | | 0.60 | 0.20 | 2 |
| 0.66 | 0.11 | 0.9 | 2.69 | 21.1 | 9.93 | 77.9 | 0.01 | 0.08 | 1.40 | | 2 |
| 0.96 | 0.11 | 0.9 | 1.75 | 14.5 | 10.16 | 84.5 | 0.00 | 0.0 | 0.10 | 0.90 | 2 |
| 0.70 | 0.11 | 1.0 | 1.71 | 14.9 | 9.64 | 84.0 | 0.02 | 0.2 | 0.10 | 0.20 | 2 |
| | 0.23 | 1.9 | 0.07 | 0.6 | 11.52 | 97.5 | 00.0 | 0.0 | 0.30 | 0.10 | 1 |
| | 0.96 | 2.4 | 22.74 | 56.4 | 16.62 | 41.2 | 0.01 | 0.00 | | 3.20 | 3 |
| 1.04 | 0.17 | 1.2 | 2.85 | 21.0 | 10.52 | 77.6 | 0.01 | 0.1 | 0.70 | 0.20 | 1 |
| 0.73 | 0.11 | 0.8 | 5.43 | 36.2 | 9.44 | 63.0 | 0.01 | 0.0 | 0.10 | 0.30 | 1 |
| 0.86 | 0.68 | 4.4 | 3.62 | 23.8 | 10.67 | 70.0 | 0.27 | 1.7 | 0.40 | 0.90 | 2 |
| 1.02 | 0.06 | 0.5 | 3.29 | 29.0 | 7.8 | 68.7 | 0.21 | 1.8 | 0.60 | 0.10 | 2 |
| 0.33 | 0.28 | 1.9 | 2.62 | 17.7 | 11.81 | 79.9 | 0.07 | 0.5 | 0.50 | 0.40 | 2 |
| 0.92 | 0.11 | 0.6 | 6.20 | 35.3 | 11.24 | 63.9 | 0.03 | 0.2 | 0.10 | 0.10 | 1 |
| 0.98 | 0.11 | 0.56 | 8.06 | 40.8 | 11.56 | 58.6 | 0.01 | 0.05 | 0.10 | 0.40 | 3 |
| 2.44 | 0.11 | 0.90 | 2.27 | 18.3 | 10.00 | 80.7 | 0.02 | 0.10 | 0.10 | 1.10 | 1 |
| 0.76 | 0.06 | 0.3 | 5.85 | 33.5 | 11.56 | 66.1 | 0.02 | 0.10 | 0.30 | 0.60 | 1 |
| 0.83 | 0.06 | 0.3 | 9.47 | 45.7 | 11.19 | 54.0 | 0.00 | 0.0 | 1.20 | 0.20 | 3 |

| Index Number | Well Depth Date Sampled (feet) | TDS ppm | Na | | K | | Ca | | Mg | | Na + K | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | epm | % | epm | % | epm | % | epm | % | epm | % |
| 6-9 | 140 3-8-78 | 740 | 13.44 | 98.8 | 0.02 | 0.2 | 0.12 | 0.9 | 0.02 | 0.1 | 13.46 | 99.0 |
| 7-1 | SPRING 4-8-78 | 768 | 10.92 | 77.6 | 0.05 | 0.35 | 1.55 | 11.0 | 1.55 | 11.0 | 10.97 | 78.0 |
| 7-3 | SPRING 4-8-78 | 862 | 14.27 | 95.2 | 0.00 | 0.0 | 0.50 | 3.4 | 0.21 | 1.4 | 14.27 | 95.2 |
| 7-5 | SPRING 4-8-78 | 402 | 2.17 | 29.9 | 0.07 | 1.0 | 3.27 | 45.1 | 1.74 | 24.0 | 2.24 | 30.9 |
| 7-6 | 78 4-8-78 | 446 | 2.87 | 36.2 | 0.10 | 1.2 | 3.39 | 42.8 | 1.56 | 19.7 | 2.97 | 37.4 |
| 7-7 | 140 4-8-78 | 520 | 0.98 | 8.7 | 0.05 | 0.4 | 5.59 | 49.6 | 3.56 | 31.6 | 1.03 | 9.1 |
| 7-8 | 205 4-8-78 | 876 | 13.88 | 83.7 | 0.01 | 0.06 | 1.22 | 7.4 | 0.76 | 4.6 | 13.89 | 83.8 |
| 8-1 | 70 7-8-78 | 1236 | 14.96 | 68.1 | 0.04 | 0.18 | 3.32 | 15.1 | 3.65 | 16.6 | 15.00 | 68.3 |
| 8-4 | 120 7-8-78 | 839 | 5.65 | 39.3 | 0.08 | 0.60 | 5.34 | 37.2 | 3.29 | 22.9 | 5.73 | 39.9 |
| 8-5 | SPRING 7-8-78 | 566 | 2.52 | 23.2 | 0.08 | 0.7 | 4.88 | 45.0 | 3.29 | 30.3 | 2.60 | 23.9 |
| 8-6 | 125 7-8-78 | 1328 | 18.05 | 77.6 | 0.01 | 0.04 | 2.65 | 11.4 | 2.55 | 11.0 | 18.06 | 78.0 |
| 8-7 | 200 7-8-78 | 654 | 5.35 | 47.3 | 0.13 | 1.1 | 4.69 | 24.7 | 3.13 | 26.9 | 5.48 | 48.4 |
| 9-1 | 123 8-8-78 | 1020 | 18.09 | 98.9 | 0.00 | 0.0 | 0.15 | 0.8 | 0.06 | 0.3 | 18.09 | 98.9 |
| 9-1B | 74 8-8-78 | 770 | 9.96 | 83.1 | 0.03 | 0.3 | 0.10 | 0.8 | 1.89 | 15.8 | 9.99 | 83.4 |
| 9-3 | SPRING 8-8-78 | 1039 | 14.27 | 76.0 | 0.00 | 0.0 | 2.20 | 11.7 | 2.3 | 12.3 | 14.27 | 76.0 |
| 9-4 | 60 8-8-78 | 964 | 2.74 | 16.7 | 0.05 | 0.3 | 5.69 | 34.7 | 7.9 | 48.2 | 2.79 | 17.0 |
| 9-6 | 180 8-8-78 | 768 | 14.05 | 98.0 | 0.00 | 0.0 | 0.20 | 1.4 | 0.08 | 0.6 | 14.05 | 98.0 |
| 9-10 | 120 8-8-78 | 1140 | 18.18 | 96.2 | 0.00 | 0.0 | 0.47 | 2.5 | 0.25 | 1.3 | 18.18 | 96.2 |
| 9-12 | 63 8-8-78 | 646 | 2.35 | 20.2 | 0.15 | 1.3 | 4.94 | 42.5 | 4.20 | 36.1 | 2.50 | 21.5 |

| Ca/Mg ratio | Cl | | $SO_4$ | | $HCO + CO$ | | NO | | Fe | F | Facies Type |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | epm | % | epm | % | epm | % | epm | % | ppm | ppm | |
| 6.00 | 0.17 | 1.3 | 1.06 | 8.0 | 12.07 | 90.6 | 0.02 | 0.2 | 0.80 | 2.60 | 1 |
| 1.00 | 0.11 | 0.80 | 3.27 | 23.6 | 10.45 | 75.4 | 0.03 | 0.21 | 0.20 | 0.70 | 1 |
| 2.38 | 0.06 | 0.40 | 2.96 | 20.2 | 11.64 | 79.4 | 0.00 | 0.0 | 0.40 | 0.40 | 1 |
| 188 | 0.17 | 2.20 | 1.01 | 13.0 | 6.57 | 84.8 | 0.00 | 0.1 | 0.50 | 0.30 | 2 |
| 2.17 | 0.17 | 2.0 | 1.09 | 12.7 | 7.24 | 84.4 | 0.08 | 1.0 | 1.10 | 0.20 | 2 |
| 1.57 | 0.11 | 1.0 | 3.37 | 30.3 | 7.64 | 68.6 | 0.00 | 0.0 | 30.5 | 0.10 | 2 |
| 1.61 | 0.17 | 1.1 | 3.77 | 21.5 | 11.52 | 75.8 | 0.13 | 0.9 | 0.20 | 1.70 | 1 |
| 0.91 | 0.17 | 0.8 | 9.54 | 45.3 | 11.28 | 53.5 | 0.07 | 0.3 | 0.10 | 0.30 | 3 |
| 1.62 | 0.28 | 1.8 | 4.75 | 31.1 | 10.24 | 67.1 | 0.00 | 0.0 | 3.7 | 0.10 | 2 |
| 1.48 | 0.17 | 1.5 | 1.71 | 14.6 | 9.83 | 83.8 | 1.3 | 0.02 | 0.40 | 0.20 | 2 |
| 1.04 | 0.68 | 2.9 | 9.93 | 42.8 | 12.12 | 52.2 | 0.48 | 2.1 | 0.40 | 0.80 | 3 |
| 1.50 | 0.56 | 4.9 | 3.08 | 27.0 | 9.38 | 64.7 | 0.38 | 3.4 | 1.50 | 0.20 | 2 |
| 2.50 | 0.11 | 0.6 | 4.06 | 23.4 | 13.16 | 75.8 | 0.04 | 0.2 | | 0.40 | 1 |
| 0.05 | 0.17 | 1.2 | 3.91 | 28.8 | 9.47 | 69.7 | 0.04 | 0.3 | | 0.40 | 1 |
| 0.96 | 0.06 | 0.3 | 5.95 | 35.4 | 11.41 | 65.5 | 0.00 | 0.0 | 0.50 | 0.20 | 1 |
| 0.72 | 0.39 | 2.4 | 4.48 | 27.5 | 10.83 | 66.7 | 0.54 | 3.3 | | 0.20 | 2 |
| 2.50 | 0.11 | 0.80 | 1.77 | 12.8 | 11.95 | 86.2 | 0.03 | 0.2 | | 1.60 | 1 |
| 1.88 | 0.17 | 0.9 | 5.60 | 31.1 | 12.19 | 67.7 | 0.05 | 0.3 | | 0.50 | 1 |
| 1.18 | 0.11 | 1.0 | 2.83 | 24.2 | 8.75 | 74.8 | 0.00 | 0.0 | | 0.10 | 2 |

| Index Number | Well Depth Date Sampled (feet) | TDS ppm | Na | | K | | Ca | | Mg | | Na + K | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | epm | % | epm | % | epm | % | epm | % | epm | % |
| 9-13 | 100 8-8-78 | 590 | 6.96 | 69.1 | 0.04 | 0.4 | 1.65 | | 1.42 | 14.1 | 7.00 | 69.5 |
| 9-14 | 130 8-8-78 | 822 | 14.96 | 98.5 | 0.00 | 0.0 | 0.19 | 1.2 | 0.03 | 0.20 | 14.96 | 98.5 |
| 9-15 | SPRING 8-8-78 | 526 | 1.74 | 18.6 | 0.05 | 0.6 | 4.59 | 49.1 | 2.96 | 31.7 | 1.79 | 19.2 |
| 10-1 | SPRING 9-8-78 | 850 | 12.88 | 85.2 | 0.01 | 0.07 | 1.55 | 10.3 | 0.67 | 4.4 | 12.89 | 85.3 |
| 10-2 | SPRING 9-8-78 | 953 | 15.18 | 90.0 | 0.01 | 0.10 | 0.77 | 4.6 | 0.91 | 5.4 | 15.19 | 90.1 |
| 10-3 | 85 9-8-78 | 982 | 14.7 | 89.3 | 0.00 | 0.0 | 0.54 | 3.3 | 1.22 | 7.4 | 14.7 | 89.3 |
| 10-4 | SPRING 9-8-78 | 928 | 9.79 | 64.7 | 0.00 | 0.0 | 2.79 | 18.5 | 2.55 | 16.9 | 9.79 | 64.7 |
| 10-5 | SPRING 9-8-78 | 832 | 12.66 | 85.5 | 0.00 | 0.0 | 1.45 | 9.8 | 0.70 | 4.7 | 12.66 | 85.5 |
| 10-6 | 50 9-8-78 | 894 | 9.18 | 62.1 | 0.01 | 0.1 | 3.04 | 20.6 | 2.55 | 17.3 | 9.19 | 62.2 |
| 10-7 | SPRING 9-8-78 | 690 | 7.83 | 63.3 | 0.00 | 0.0 | 2.64 | 21.4 | 1.89 | 15.3 | 7.83 | 63.3 |
| 10-8 | SPRING 9-8-78 | 642 | 3.96 | 33.1 | 0.01 | 0.1 | 3.64 | | 4.36 | | 3.97 | 33.2 |
| 10-9 | 180 9-8-78 | 828 | 14.62 | 98.9 | 0.00 | 0.0 | 0.12 | 0.8 | 0.03 | 0.2 | 14.62 | 98.9 |
| 10-10 | 107 9-8-78 | 836 | 11.92 | 83.9 | 0.00 | 0.0 | 0.56 | 4.0 | 1.73 | 12.2 | 11.92 | 83.9 |
| 11-1 | 170 10-8-78 | 695 | 12.01 | 99.2 | 0.00 | 0.0 | 0.07 | 0.6 | 0.02 | 0.10 | 12.01 | 99.2 |
| 11-2 | SPRING 10-8-78 | 678 | 11.53 | 97.0 | 0.00 | 0.0 | 0.23 | 2.0 | 0.12 | 1.0 | 11.53 | 97.0 |
| 11-3 | SPRING 10-8-78 | 808 | 12.66 | 92.0 | 0.03 | 0.2 | 0.43 | 3.1 | 0.63 | 4.6 | 12.69 | 92.2 |
| 11-6 | 170 10-8-78 | 732 | 12.44 | 97.4 | 0.02 | 0.2 | 0.21 | 1.6 | 0.10 | 0.8 | 12.46 | 97.6 |
| 11-7 | SPRING 10-8-78 | 388 | 1.85 | 21.6 | 0.06 | 0.7 | 3.72 | 43.5 | 2.92 | 34.2 | 1.91 | 22.3 |
| 11-8 | 105 10-8-78 | 770 | 13.61 | 98.1 | 0.01 | 0.1 | 0.19 | 1.4 | 0.06 | 0.4 | 13.62 | 98.2 |

| Ca/Mg ratio | Cl epm | Cl % | $SO_4$ epm | $SO_4$ % | $HCO_3 - CO_3$ epm | $HCO_3 - CO_3$ % | $NO_3$ epm | $NO_3$ % | Fe ppm | F ppm | Facies Type |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.16 | 0.11 | 1.1 | 2.02 | 19.5 | 8.16 | 78.8 | 0.06 | 0.6 | | 0.20 | 1 |
| 6.33 | 0.11 | 0.8 | 2.48 | 16.9 | 12.08 | 82.2 | 0.03 | 0.2 | | 0.40 | 1 |
| 1.47 | 0.11 | 1.1 | 1.37 | 14.0 | 8.36 | 84.9 | 0.00 | 0.0 | | 0.20 | 2 |
| 2.31 | 0.11 | 0.7 | 3.04 | 20.2 | 11.67 | 77.6 | 0.21 | 1.4 | 1.10 | 0.50 | 1 |
| 0.85 | 0.06 | 0.4 | 4.62 | 28.7 | 11.39 | 70.8 | 0.03 | 0.2 | | 0.30 | 1 |
| 0.44 | 0.06 | 0.4 | 5.10 | 31.7 | 10.92 | 67.9 | 0.01 | 0.1 | | 0.40 | 1 |
| 1.02 | 0.11 | 0.8 | 3.39 | 23.1 | 11.19 | 76.1 | 0.00 | 0.0 | 0.00 | 0.20 | 1 |
| 2.07 | 0.06 | 0.4 | 3.04 | 21.1 | 11.24 | 78.2 | 0.04 | 0.3 | 0.30 | 0.90 | 1 |
| 1.19 | 0.11 | 0.7 | 3.83 | 25.4 | 11.11 | 73.8 | 0.00 | 0.0 | | 0.30 | 1 |
| 1.40 | 0.06 | 0.5 | 2.17 | 17.6 | 10.11 | 82.0 | 0.00 | 0.0 | 0.00 | 0.20 | 1 |
| 0.84 | 0.06 | 0.5 | 1.64 | 14.3 | 9.75 | 84.9 | 0.04 | 0.3 | | 0.10 | 2 |
| 4.00 | 0.11 | 0.8 | 2.96 | 21.4 | 10.71 | 77.6 | 0.02 | 0.2 | | 1.60 | 1 |
| 0.33 | 0.06 | 0.4 | 3.96 | 29.0 | 9.6 | 70.4 | 0.02 | 0.2 | | 0.20 | 1 |
| 3.50 | 0.34 | 2.6 | 1.06 | 8.2 | 11.52 | 89.0 | 0.02 | 0.2 | | 1.20 | 1 |
| 1.97 | 0.06 | 0.5 | 1.60 | 13.7 | 10.07 | 85.8 | 0.00 | 0.0 | | 0.50 | 1 |
| 0.68 | 0.06 | 0.4 | 3.33 | 24.8 | 10.24 | | 0.02 | 0.2 | | 0.70 | 1 |
| 2.10 | 0.06 | 0.5 | 2.19 | 17.8 | 10.00 | 81.4 | 0.04 | 0.3 | | 0.80 | 1 |
| 1.27 | 0.06 | 0.65 | 0.83 | 9.0 | 8.29 | 89.7 | 0.06 | 0.65 | 0.10 | 0.20 | 2 |
| 3.17 | 0.23 | 1.7 | 1.85 | 13.6 | 11.48 | 84.5 | 0.02 | 0.10 | | 1.10 | 1 |

| Index Number | Well Depth Date Sampled (feet) | TDS ppm | Na | | K | | Ca | | Mg | | Na + K | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | epm | % | epm | % | epm | % | epm | % | epm | % |
| 11-9 | SPRING 10-8-78 | 396 | 1.69 | 21.5 | 0.06 | 0.8 | 2.30 | 29.3 | 3.79 | 48.3 | 1.75 | 22.3 |
| 11-10 | SPRING 10-8-78 | 814 | 9.96 | 68.8 | 0.04 | 0.3 | 2.25 | 15.5 | 2.22 | 15.4 | 10.00 | 68.9 |
| 12-1 | SPRING 11-8-78 | 734 | 7.87 | 58.1 | 0.06 | 0.5 | 2.74 | 20.2 | 2.88 | 21.2 | 7.93 | 58.6 |
| 12-2 | SPRING 11-8-78 | 844 | 10.40 | 69.6 | 0.04 | 0.3 | 1.95 | 13.0 | 2.55 | 17.1 | 10.44 | 69.9 |
| 12-3 | 255 11-8-78 | 846 | 14.75 | 96.5 | 0.00 | 0.0 | 0.30 | 2.0 | 0.24 | 1.6 | 14.75 | 96.5 |
| 12-4 | 100 11-8-78 | 460 | 3.61 | 41.9 | 0.04 | 0.5 | 1.10 | 12.7 | 3.87 | 44.9 | 3.65 | 42.4 |
| 12-5 | SPRING 11-8-78 | 722 | 9.26 | 75.7 | 0.05 | 0.4 | 0.12 | 1.0 | 2.8 | 22.9 | 9.31 | 76.1 |
| 12-7 | 180 11-8-78 | 1008 | 16.79 | 98.6 | 0.00 | 0.0 | 0.17 | 1.0 | 0.07 | 0.4 | 16.79 | 98.6 |
| 12-8 | 72 11-8-78 | 296 | 2.39 | 48.7 | 0.02 | 0.4 | 0.92 | 18.8 | 1.58 | 32.1 | 2.41 | 49.1 |
| 13-1 | 80 15-8-78 | 430 | 1.04 | 12.5 | 0.07 | 0.9 | 3.44 | 41.7 | 3.7 | 44.9 | 1.11 | 13.4 |
| 13-2 | SPRING 15-8-78 | 370 | 2.35 | 34.5 | 0.06 | 0.9 | 2.35 | 34.4 | 2.06 | 30.2 | 2.41 | 35.4 |
| 13-4 | SPRING 15-8-78 | 356 | 1.36 | 18.4 | 0.05 | 0.7 | 3.09 | 41.9 | 2.88 | 39.0 | 1.41 | 19.1 |
| 13-5 | SPRING 15-8-78 | 660 | 6.26 | 50.4 | 0.03 | 0.3 | 2.99 | 24.1 | 3.13 | 25.2 | 6.29 | 50.7 |
| 14-1 | 175 17-8-78 | 902 | 11.53 | 70.0 | 0.00 | 0.0 | 3.44 | 20.9 | 1.49 | 9.1 | 11.53 | 70.0 |
| 14-2 | 90 17-8-78 | 750 | 12.61 | 89.4 | 0.00 | 0.0 | 1.10 | 7.8 | 0.40 | 2.8 | 12.61 | 89.4 |
| 14-3 | 37 17-8-78 | 358 | 2.78 | 31.8 | 0.02 | 0.2 | 3.93 | 45.0 | 2.00 | 22.9 | 2.80 | 32.0 |
| 14-4 | SPRING 17-8-78 | 578 | 6.92 | 61.4 | 0.05 | 0.5 | 2.94 | 26.1 | 1.35 | 12.0 | 6.97 | 61.9 |
| 14-5 | 98 17-8-79 | 616 | 8.39 | 67.4 | 0.04 | 0.3 | 2.61 | 21.0 | 1.40 | 11.3 | 8.43 | 67.7 |
| 14-6 | 80 17-8-78 | 664 | 5.92 | 46.5 | 0.06 | 0.47 | 4.65 | 36.5 | 2.10 | 16.5 | 5.98 | 46.97 |

| Ca/Mg ratio | Cl epm | Cl % | $SO_4$ epm | $SO_4$ % | $HCO_3 + CO_3$ epm | $HCO_3 + CO_3$ % | $NO_3$ epm | $NO_3$ % | Fe ppm | F ppm | Facies Type |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.61 | 0.17 | 2.1 | 0.92 | 11.4 | 6.92 | 86.2 | 0.02 | 0.20 | | 0.10 | 2 |
| 1.01 | 0.11 | 0.8 | 2.96 | 21.4 | 10.72 | 77.5 | 0.04 | 0.3 | | 0.20 | 1 |
| 0.95 | 0.06 | 0.4 | 2.67 | 20.4 | 10.31 | 79.1 | 0.01 | 0.1 | | 0.10 | 2 |
| 0.77 | 0.17 | 1.1 | 3.44 | 23.2 | 11.08 | 74.9 | 0.11 | 0.8 | | 0.10 | 1 |
| 1.25 | 0.06 | 0.4 | 2.81 | 19.1 | 11.80 | 80.2 | 0.05 | 0.3 | | 0.20 | 1 |
| 0.28 | 0.11 | 1.3 | 1.31 | 14.6 | 7.56 | 84.1 | 0.00 | 0.1 | | 0.10 | 2 |
| 0.04 | 0.11 | 0.9 | 2.56 | 20.1 | 10.00 | 78.5 | 0.06 | 0.5 | | 0.10 | 1 |
| 2.43 | 0.06 | 0.3 | 4.06 | 24.9 | 12.16 | 74.6 | 0.03 | 0.2 | | 0.40 | 1 |
| 0.58 | 0.17 | 3.2 | 0.51 | 9.5 | 4.63 | 86.3 | 0.05 | 1.0 | | 0.30 | 2 |
| 0.94 | 0.28 | 3.3 | 0.67 | 8.0 | 7.11 | 83.8 | 0.41 | 4.9 | 0.70 | 0.10 | 2 |
| 1.21 | 0.17 | 2.3 | 0.51 | 7.0 | 6.67 | 90.6 | 0.00 | 0.1 | 0.30 | 0.10 | 2 |
| 1.14 | 0.11 | 1.5 | 0.51 | 6.7 | 6.97 | 91.4 | 0.03 | 0.4 | 0.60 | 0.10 | 2 |
| 1.08 | 0.11 | 0.9 | 3.41 | 27.0 | 9.11 | 72.1 | 0.01 | 0.1 | 0.30 | 0.10 | 2 |
| 2.39 | 0.34 | 2.2 | 3.33 | 21.3 | 11.92 | 76.3 | 0.04 | 0.2 | 0.20 | 0.60 | 1 |
| 2.75 | 0.11 | 0.8 | 1.96 | 13.8 | 12.03 | 85.1 | 0.04 | 0.3 | 0.10 | 0.40 | 1 |
| 1.97 | 0.34 | 3.7 | 1.04 | 11.3 | 7.83 | 84.9 | 0.01 | 0.1 | 0.90 | 0.20 | 2 |
| 2.13 | 0.06 | 0.5 | 1.52 | 13.6 | 9.52 | 85.5 | 0.04 | 0.4 | 2.70 | 0.30 | 1 |
| 1.86 | 0.06 | 0.49 | 1.79 | 14.5 | 10.47 | 84.9 | 0.01 | 0.08 | 0.40 | 0.40 | 1 |
| 2.21 | 0.11 | 0.90 | 3.29 | 26.9 | 8.80 | 71.8 | 0.05 | 0.41 | 5.70 | 0.20 | 2 |

| Index Number | Well Depth Date Sampled (feet) | TDS ppm | Na | | K | | Ca | | Mg | | Na + K | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | epm | % | epm | % | epm | % | epm | % | epm | % |
| 14-8 | 17-8-78 | 910 | 16.09 | 98.7 | 0.00 | 0.0 | 0.18 | 1.1 | 0.02 | 0.2 | 16.09 | 98.7 |
| 14-9 | SPRING 17-8-78 | 734 | 12.61 | 97.4 | 0.00 | 0.0 | 0.26 | 2.0 | 0.07 | 0.6 | 12.61 | 97.4 |
| 14-10 | 125 17-8-78 | 1412 | 22.75 | 96.8 | 0.00 | 0 0 | 0.57 | 2.4 | 0.17 | 0.7 | 22.75 | 96.8 |
| 14-11 | SPRING 17-8-78 | 972 | 14.14 | 79.7 | 0.00 | 0.0 | 2.55 | 14.4 | 1.05 | 5.9 | 14.14 | 79.7 |
| 14-12 | 80 17-8-78 | 1350 | 22.23 | 96.8 | 0.03 | 0.13 | 0.471 | 2.1 | 0.17 | 0.74 | 22.26 | 96.9 |
| 15-1 | SPRING 18-8-78 | 340 | 1.85 | 26.9 | 0.07 | 1.1 | 3.04 | 44.4 | 1.89 | 27.6 | 1.92 | 28.0 |
| 15-2 | 200 18-8-78 | 1018 | 18.40 | 98.4 | 0.02 | 0.1 | 0.23 | 1.3 | 0.07 | 0.4 | 18.42 | 98.5 |
| 15-3 | 300 18-8-78 | 764 | 14.05 | 98.7 | 0.01 | 0.1 | 0.14 | 1.0 | 0.05 | 0.2 | 14.06 | 98.8 |
| 15-4 | 200 18-8-78 | 798 | 14.05 | 98.8 | 0.00 | 0.0 | 0.14 | 10.0 | 0.03 | 0.2 | 14.05 | 98.8 |
| 15-5 | 200 18-8-78 | 1268 | 19.92 | 95.2 | 0.04 | 0.2 | 0.60 | 2.9 | 0.36 | 1.7 | 19.96 | 95.4 |
| 15-6 | 198 18-8-78 | 1224 | 19.27 | 92.9 | 0.19 | 0.9 | 0.93 | 4.5 | 0.36 | 1.7 | 19.46 | 93.8 |
| 15-7 | 242 18-8-78 | 754 | 12.74 | 97.4 | 0.00 | 0.0 | 0.24 | 1.8 | 0.10 | 0.8 | 12.74 | 97.4 |
| 15-8 | 60 18-8-78 | 1479 | 24.05 | 92.2 | 0.04 | 0.2 | 1.35 | 5.2 | 0.64 | 2.5 | 24.09 | 92.4 |
| 15-10 | 90 18-8-78 | 914 | 13.92 | 92.5 | 0.00 | 0.0 | 0.79 | 5.3 | 0.34 | 2.2 | 13.92 | 92.5 |
| 15-11 | SPRING 18-8-78 | 348 | 0.60 | 8.4 | 0.25 | 3.5 | 4.49 | 63.0 | 1.78 | 25.0 | 0.85 | 11.9 |
| 15-12 | 85 18-8-78 | 1212 | 19.14 | 96.6 | 0.00 | 0.0 | 0.48 | 2.4 | 0.18 | 0.9 | 19.14 | 96.6 |
| 15-13 | 80 18-8-78 | 1144 | 18.40 | 98.4 | 0.00 | 0.0 | 0.22 | 1.2 | 0.07 | 0.4 | 18.44 | 98.4 |
| 16.2 | SPRING 19-8-78 | 624 | 4.31 | 34.2 | 0.04 | 0.3 | 4.60 | 36.5 | 3.65 | 29.0 | 4.35 | 34.5 |
| 16-3 | 100 19-8-78 | 1038 | 13.01 | 76.8 | 0.00 | 0.0 | 2.69 | 15.9 | 1.23 | 7.2 | 13.01 | 76.8 |

| Ca/Mg ratio | Cl epm | Cl % | $SO_4$ epm | $SO_4$ % | $HCO_3 + CO_3$ epm | $HCO_3 + CO_3$ % | $NO_3$ epm | $NO_3$ % | Fe ppm | F ppm | Facies Type |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 9.00 | 0.11 | 0.70 | 5.04 | 32.5 | 10.31 | 66.5 | 0.03 | 0.2 | 0.10 | 0.80 | 1 |
| 3.95 | 0.11 | 0.90 | 1.92 | 15.2 | 10.56 | 83.8 | 0.02 | 0.2 | 0.10 | 0.50 | 1 |
| 3.34 | 0.06 | 0.30 | 6.58 | 30.4 | 14.95 | 69.1 | 0.04 | 0.2 | 0.90 | 0.40 | 1 |
| 2.43 | 0.06 | 0.35 | 4.73 | 27.8 | 12.15 | 71.5 | 0.05 | 0.3 | 0.30 | 0.20 | 1 |
| 2.77 | 0.06 | 0.26 | 7.35 | 32.0 | 14.69 | 64.0 | 0.05 | 0.22 | 1.80 | 0.30 | 1 |
| 1.70 | 0.23 | 3.2 | 0.51 | 7.2 | 6.28 | 89.0 | 0.04 | 0.6 | 0.00 | 0.20 | 2 |
| 3.19 | 0.11 | 0.6 | 3.25 | 18.3 | 14.28 | 80.5 | 0.03 | 0.2 | 0.10 | 1.30 | 1 |
| 3.16 | 0.23 | 1.7 | 2.62 | 19.7 | 10.45 | 78.4 | 0.02 | 0.2 | 0.00 | 1.10 | 1 |
| 6.75 | 0.17 | 1.2 | 3.29 | 23.8 | 10.31 | 74.8 | 0.02 | 0.2 | 0.30 |  | 1 |
| 1.71 | 0.11 | 0.6 | 8.06 | 42.2 | 10.88 | 57.0 | 0.05 | 0.3 | 0.10 | 0.40 | 3 |
| 2.61 | 0.17 | 0.9 | 6.00 | 30.7 | 13.31 | 68.2 | 0.04 | 0.2 | 0.30 | 0.50 | 1 |
| 2.48 | 0.11 | 0.8 | 5.29 | 36.9 | 8.88 | 62.0 | 0.05 | 0.4 | 0.10 | 0.90 | 1 |
| 3.09 | 0.11 | 0.5 | 9.60 | 40.9 | 13.72 | 58.4 | 0.06 | 0.3 | 1.80 | 0.30 | 3 |
| 2.41 | 0.11 | 0.8 | 3.77 | 27.2 | 9.92 | 71.7 | 0.04 | 0.3 | 0.30 | 0.70 | 1 |
| 2.52 | 0.45 | 5.9 | 0.62 | 8.2 | 6.2 | 81.9 | 0.30 | 4.0 | 0.10 | 0.10 | 2 |
| 2.62 | 0.06 | 0.3 | 6.12 | 33.4 | 12.11 | 66.1 | 0.03 | 0.2 | 0.10 | 0.40 | 1 |
| 2.55 | 0.17 | 0.9 | 6.00 | 32.6 | 12.19 | 66.3 | 0.03 | 0.2 | 0.00 | 0.40 | 1 |
| 1.26 | 0.11 | 0.9 | 2.83 | 23.0 | 9.36 | 76.0 | 0.01 | 0.08 | 0.00 | 0.10 | 2 |
| 2.20 | 0.06 | 0.3 | 6.02 | 36.3 | 10.44 | 63.0 | 0.06 | 0.4 | 1.50 | 0.10 | 1 |

| Index Number | Well Depth Date Sampled (feet) | TDS ppm | Na | | K | | Ca | | Mg | | Na + K | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | epm | % | epm | % | epm | % | epm | % | epm | % |
| 16-4 | 125 19-8-78 | 1578 | 25.14 | 97.8 | 0.01 | 0.0 | 0.45 | 1.7 | 0.11 | 0.4 | 25.14 | 97.8 |
| 16-6 | 200 19-8-78 | 1298 | 22.36 | 97.9 | 0.02 | 0.1 | 0.36 | 1.6 | 0.10 | 0.4 | 22.38 | 98.0 |
| P-1 | CREEK 1-11-77 | 700 | 9.79 | 74.7 | 0.15 | 1.1 | 1.11 | 8.5 | 2.06 | 15.7 | 9.94 | 75.8 |

| Ca/Mg ratio | Cl | | $SO_4$ | | $HCO_3$ + $CO_3$ | | NO | | Fe | F | Facies Type |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | epm | % | epm | % | epm | % | epm | % | ppm | ppm | |
| 3.92 | 0.11 | 0.5 | 10.58 | 43.5 | 13.56 | 55.9 | 0.05 | 0.2 | 0.30 | 0.20 | 2 |
| 3.34 | 0.17 | 0.8 | 7.75 | 35.9 | 13.64 | 63.1 | 0.05 | 0.2 | 0.40 | 0.40 | 1 |
| 0.54 | 0.11 | 0.9 | 3.66 | 27.7 | 9.45 | 71.5 | 0.00 | 0.0 | | 0.40 | 1 |

## APPENDIX C: Deep Well Data

Notes to Appendix C

1. Column 1: The letter in the index indicates the following type of well: S = structure test hole, C = coal test hole and H = gas or oil test hole.
2. Column 3: Datum elevation refers to the elevation from which the geophysical well logs are measured as zero depth. In most cases this is a surveyed land or ground elevation. The letters G.L. beside the number indicate ground level, while the letter K.B. indicate a Kelly Bushing elevation.
3. Columns 6 to 8: The abbreviation L. Ardley 'B' stands for Lower Ardley 'B' coal zone.
4. Columns 9 and 10: These columns refer to the amount of sandstone (cumulative) in the strata above the Lower Ardley 'B' coal zone.

| Elevation of L. Ardley 'B' (feet) | Thickness of L. Ardley 'B' (feet) | Thickness of Sandstone (feet) | Percent Sandstone | Depth to Bedrock (feet) |
|---|---|---|---|---|
| 2612 | 16 | 270 | 79 | |
| 2593 | 17 | 100 | 48 | |
| 2583 | 18 | 136 | 37 | |
| 2584 | 20 | 200 | 61 | 107 |
| 2529 | 17 | 213 | 45 | |
| 2601 | 18 | 128 | 67 | 48 |
| 2609 | 16 | 160 | 44 | |
| 2599 | 17 | 262 | 66 | 20 |
| 2507 | 19 | 262 | 54 | |
| 2508 | 18 | 160 | 29 | |
| 2508 | 17 | 200 | 17 | |
| 2468 | 21 | 130 | 21 | |
| 2484 | 17 | 150 | 26 | |
| 2487 | 17 | 224 | 41 | |
| 2453 | 17 | 324 | 50 | |
| 2462 | 21 | 335 | 56 | |
| 2443 | 21 | 228 | 37 | 83 |
| 2448 | 19 | 260 | 39 | 89 |
| 2427 | 21 | 320 | 45 | |
| 2466 | 20 | 285 | 42 | 36 |
| 2545 | 17 | 185 | 43 | |
| 2515 | 17 | 170 | 47 | 60 |

| Index Number | Location | Datum Elevation (feet) | Depth Logged (feet) | Company Date | Depth to top of L. Ardley 'B' (feet) |
|---|---|---|---|---|---|
| S-1 | 13-36-34-24W4 | 3003 | 855 | July 19, 1953 | 391 |
| S-2 | 15-34-34-24W4 | 2850 | 650 | July 14, 1953 | 257 |
| S-3 | 3-3-35-24W4 | 3000 | 755 | July 17, 1953 | 415 |
| S-4 | 2-4-35-24W4 | 2960 | 758 | June 9, 1953 | 376 |
| S-5 | 13-6-35-24W4 | 3055 | 905 | Gulf Oil Nov. 3, 1952 | 526 |
| S-6 | 9-10-35-24W4 | 2842 | 770 | June 9, 1953 | 241 |
| S-7 | 9-13-35-24W4 | 3020 | 862 | July 13, 1953 | 411 |
| S-8 | 1-14-35-24W4 | 3045 | 843 | June 8, 1953 | 446 |
| S-9 | 13-2-35-25W4 | 3042 | 919 | Gulf Oil Nov. 8, 1952 | 535 |
| S-10 | 13-12-35-25W4 | 3109 | 960 | Gulf Oil Oct. 31, 1952 | 601 |
| S-11 | 16-12-35-25W4 | 3104 | 906 | Gulf Oil Nov. 2, 1952 | 596 |
| S-12 | 4-23-35-25W4 | 3152 | 1059 | Gulf Oil Oct. 25, 1952 | 684 |
| S-13 | 4-24-35-25W4 | 3106 | 1006 | Gulf Oil Oct. 22, 1952 | 622 |
| S-14 | 16-24-35-25W4 | 3057 | 967 | Gulf Oil Oct. 29, 1952 | 570 |
| S-15 | 4-26-35-25W4 | 3152 | 804 | Chevron Aug. 27, 1951 | 699 |
| S-16 | 4-27-35-25W4 | 3116 | 774 | Chevron Sept. 14, 1951 | 654 |
| S-17 | 4-28-35-25W4 | 3109 | 803 | Chevron Aug. 23, 1951 | 666 |
| S-18 | 13-32-35-25W4 | 3167 | 909 | Chevron Aug. 21, 1951 | 719 |
| S-19 | 4-33-35-25W4 | 3183 | 814 | Chevron Oct. 30, 1951 | 756 |
| S-20 | 4-34-35-25W4 | 3191 | 800 | Chevron Oct. 17, 1953 | 725 |
| S-21 | 1-4-36-24W4 | 3025 | 627 | Chevron Aug. 21, 1951 | 480 |
| S-22 | 13-32-35-24W4 | 2928 | 569 | Chevron Aug. 17, 1951 | 413 |

| Index Number | Location | Datum Elevation (feet) | Depth Logged (feet) | Company Date | Depth to top of L. Ardley 'B' (feet) |
|---|---|---|---|---|---|
| S-23 | 13-7-36-24W4 | 2970 | 556 | Chevron Nov. 13, 1951 | 484 |
| S-24 | 13-11-36-24W4 | 3050 | 553 | Chevron Dec. 2, 1951 | 479 |
| S-25 | 4-16-36-24W4 | 3057 | 600 | Chevron Dec. 2, 1951 | 528 |
| S-26 | 12-24-36-24W4 | 2710 | 416 | Royalite Oil Aug. 23, 1952 | |
| S-27 | 13-24-36-24W4 | 3052 | 526 | Royalite Oil June 19, 1952 | 503 |
| S-28 | 4-26-36-24W4 | 3053 | 606 | Chevron Nov. 7, 1951 | 489 |
| S-29 | 4-27-36-24W4 | 3122 | 636 | Royalite Oil Sept. 11, 1952 | 591 |
| S-30 | 1-30-36-24W4 | 3000 | 557 | Royalite Oil Sept. 16, 1952 | 503 |
| S-31 | 13-35-36-24W4 | 2981 | 490 | Royalite Oil July 3, 1952 | 427 |
| S-32 | 4-1-36-25W4 | 3022 | 701 | Chevron Aug. 16, 1951 | 557 |
| S-33 | 4-2-36-25W4 | 3088 | 711 | Chevron Sept. 21, 1951 | 619 |
| S-34 | 4-3-36-25W4 | 3136 | 850 | Chevron Aug. 14, 1951 | 709 |
| S-35 | 4-4-36-25W4 | 3211 | 851 | Chevron Sept. 14, 1951 | 775 |
| S-36 | 4-6-36-25W4 | 3044 | 676 | Chevron Oct. 28, 1951 | 609 |
| S-37 | 4-7-36-25W4 | 3090 | 755 | Chevron Sept. 18, 1951 | 657 |
| S-38 | 13-7-36-25W4 | 3143 | 804 | Chevron Sept. 18, 1953 | 729 |
| S-39 | 4-8-36-25W4 | 3148 | 786 | Chevron Sept. 25, 1951 | 731 |
| S-40 | 16-8-36-25W4 | 3239 | 901 | Chevron Aug. 29, 1951 | 798 |
| S-41 | 4-11-36-25W4 | 3068 | 1018 | Chevron Nov. 28, 1951 | 599 |

| Elevation of L. Ardley 'B' (feet) | Thickness of L. Ardley 'B' (feet) | Thickness of Sandstone (feet) | Percent Sandstone | Depth to Bedrock (feet) |
|---|---|---|---|---|
| 2486 | 15 | 120 | 28 | |
| 2571 | 15 | 215 | 50 | |
| 2529 | 15 | 182 | 38 | |
| 2549 | 14 | 226 | 50 | 42 |
| 2564 | 14 | 162 | 37 | |
| 2531 | 14 | 248 | 46 | |
| 2497 | 14 | 175 | 39 | 55 |
| 2554 | 14 | 150 | 40 | 50 |
| 2465 | 16 | 208 | 41 | |
| 2469 | 17 | 220 | 39 | |
| 2427 | 23 | 246 | 37 | |
| 2436 | 20 | 406 | 56 | |
| 2435 | 21 | 270 | 48 | 86 |
| 2433 | 19 | 328 | 54 | |
| 2414 | 19 | 296 | 44 | 70 |
| 2417 | 19 | 330 | 49 | 77 |
| 2441 | 16 | 290 | 39 | |
| 2469 | 17 | 100 | 18 | |

| Index Number | Location | Datum Elevation (feet) | Depth Logged (feet) | Company Date | Depth to top of L. Ardley 'B' (feet) |
|---|---|---|---|---|---|
| S-42 | 4-14-36-25W4 | 3012 | 607 | Chevron Nov. 8, 1951 | 560 |
| S-43 | 13-15-36-25W4 | 3113 | 1042 | Chevron Nov. 24, 1951 | 661 |
| S-44 | 4-17-36-25W4 | 3220 | 849 | Chevron Sept. 21, 1951 | 797 |
| S-45 | 4-18-36-25W4 | 3148 | 850 | Chevron Sept. 6, 1951 | 790 |
| S-46 | 4-18-36-25W4 | 3148 | 1253 | Chevron Nov. 20, 1951 | 791 |
| S-47 | 13-19-36-25W4 | 3171 | 1248 | Chevron Oct. 16, 1951 | 774 |
| S-48 | 13-20-36-25W4 | 3193 | 852 | Chevron Sept. 11, 1951 | 774 |
| S-49 | 13-22-36-25W4 | 3038 | 682 | Chevron Nov. 1, 1951 | 559 |
| S-50 | 13-23-36-25W4 | 2925 | 550 | Chevron Nov. 4, 1951 | 443 |
| S-51 | 1-25-36-25W4 | 3008 | 548 | Chevron Nov. 5, 1951 | 517 |
| S-52 | 9-26-36-25W4 | 2990 | 624 | Chevron Dec. 11, 1951 | 505 |
| S-53 | 1-26-36-25W4 | 2969 | 540 | Chevron Dec. 20, 1951 | 487 |
| S-54 | 3-26-36-25W4 | 2970 | 575 | Royalite Oil Sept. 16, 1952 | 491 |
| S-55 | 5-28-36-25W4 | 3112 | 740 | Chevron Nov. 5, 1951 | 668 |
| S-56 | 13-32-36-25W4 | 3123 | 1090 | Chevron Nov. 23, 1951 | 718 |
| S-57 | 1-33-36-25W4 | 3035 | 602 | Chevron Dec. 21, 1951 | 564 |
| S-58 | 4-35-36-25W4 | 2945 | 553 | Chevron Dec. 19, 1951 | 471 |
| S-59 | 4-12-36-26W4 | 3024 | 744 | Chevron Nov. 2, 1951 | 609 |
| S-60 | 1-14-36-26W4 | 3049 | 801 | Chevron 1951 | 636 |

| Elevation of L. Ardley 'B' (feet) | Thickness of L. Ardley 'B' (feet) | Thickness of Sandstone (feet) | Percent Sandstone | Depth to Bedrock (feet) |
|---|---|---|---|---|
| 2452 | 15 | 102 | 20 | 60 |
| 2452 | 18 | 182 | 30 | |
| 2423 | 17 | 330 | 44 | |
| 2358 | 26 | 282 | 38 | 70 |
| 2357 | 25 | 290 | 39 | 66 |
| 2397 | 17 | 182 | 25 | 70 |
| 2419 | 18 | 162 | 22 | |
| 2479 | 18 | 124 | 24 | |
| 2482 | 19 | 128 | 33 | 137 |
| 2491 | 16 | 116 | 25 | |
| 2485 | 16 | 146 | 32 | 80 |
| 2482 | 15 | 114 | 26 | |
| 2479 | 15 | 138 | 31 | 52 |
| 2444 | 16 | 170 | 28 | 96 |
| 2405 | 20 | 234 | 35 | |
| 2471 | 17 | 212 | 41 | 85 |
| 2474 | 15 | 164 | 39 | 138 |
| 2415 | 20 | 256 | 46 | |
| 2413 | 20 | | | |

| Index Number | Location | Datum Elevation (feet) | Depth Logged (feet) | Company Date | Depth to top of L. Ardley 'B' (feet) |
|---|---|---|---|---|---|
| S-61 | 1-26-36-26W4 | 3136 | 870 | Chevron Sept. 11, 1951 | 735 |
| S-62 | 13-27-36-26W4 | 3201 | 1320 | Gulf Oct. 21, 1954 | 852 |
| S-63 | 4-6-37-24W4 | 3187 | 801 | Royalite Oil Sept. 16, 1952 | 689 |
| S-64 | 4-6-37-24W4 | 3187 | 739 | Chevron Nov. 12, 1951 | 690 |
| S-65 | 13-7-37-24W4 | 3020 | 564 | Chevron Oct. 18, 1953 | 498 |
| S-66 | 4-17-37-24W4 | 2960 | 554 | Royalite Oil June 7, 1952 | 419 |
| S-67 | 4-18-37-24W4 | 2973 | 634 | Chevron Jan. 3, 1952 | 468 |
| S-68 | 13-1-37-25W4 | 3144 | 700 | Chevron Oct. 11, 1953 | 658 |
| S-69 | 13-2-37-25W4 | 3115 | 689 | Chevron Sept. 16, 1953 | 642 |
| S-70 | 1-3-37-25W4 | 3027 | 630 | Chevron Nov. 10, 1951 | 571 |
| S-71 | 13-4-37-25W4 | 3150 | 743 | Chevron Oct. 11, 1953 | 696 |
| S-72 | 2-5-37-25W4 | 3111 | 745 | Chevron Dec. 7, 1951 | 649 |
| S-73 | 16-5-37-25W4 | 3169 | 808 | Chevron Dec. 22, 1951 | 711 |
| S-74 | 4-6-37-25W4 | 3168 | 847 | Chevron Nov. 29, 1951 | 786 |
| S-75 | 1-10-37-25W4 | 3150 | 731 | Chevron Dec. 12, 1951 | 679 |
| S-76 | 5-10-37-25W4 | 3060 | 700 | Chevron Sept. 11, 1953 | 592 |
| S-77 | 13-11-37-25W4 | 3134 | 703 | Chevron Sept. 15, 1953 | 653 |
| S-78 | 13-12-37-25W4 | 3032 | 660 | Chevron Dec. 1, 1951 | 573 |
| S-79 | 1-14-37-25W4 | 3015 | 575 | Royalite Oil June 9, 1952 | 522 |

| Elevation of L. Ardley 'B' (feet) | Thickness of L. Ardley 'B' (feet) | Thickness of Sandstone (feet) | Percent Sandstone | Depth to Bedrock (feet) |
|---|---|---|---|---|
| 2401 | 18 | 268 | 39 | |
| 2349 | 20 | 360 | 45 | |
| 2498 | 14 | 286 | 45 | |
| 2497 | 17 | 245 | 38 | |
| 2522 | 13 | 130 | 29 | 150 |
| 2541 | 14 | 146 | 40 | 108 |
| 2505 | 14 | 140 | 34 | 98 |
| 2486 | 15 | 214 | 35 | 68 |
| 2473 | 16 | 264 | 45 | |
| 2456 | 17 | 240 | 46 | 57 |
| 2454 | 14 | 248 | 38 | 36 |
| 2462 | 15 | 168 | 28 | 63 |
| 2458 | 15 | 236 | 36 | 52 |
| 2382 | 17 | 170 | 23 | 66 |
| 2471 | 17 | 290 | 46 | |
| 2468 | 15 | 186 | 34 | 132 |
| 2481 | 16 | 196 | 33 | 130 |
| 2459 | 15 | 192 | 37 | 114 |
| 2493 | 14 | 198 | 42 | 126 |

| Index Number | Location | Datum Elevation (feet) | Depth Logged (feet) | Company Date | Depth to top of L. Ardley 'B' (feet) |
|---|---|---|---|---|---|
| S-80 | 13-14-37-25W4 | 3037 | 612 | Chevron Dec. 16, 1951 | 573 |
| S-81 | 1-15-37-25W4 | 3095 | 732 | Chevron Dec. 14, 1951 | 628 |
| S-82 | 4-15-37-25W4 | 3133 | 1102 | Chevron Nov. 27, 1951 | 640 |
| S-83 | 4-15-37-25W4 | 3134 | 659 | Chevron Oct. 6, 1953 | 640 |
| S-84 | 4-15-37-25W4 | 3134 | 777 | Royalite Oil June 10, 1952 | 639 |
| S-85 | 7-15-37-25W4 | 3098 | 663 | Chevron Nov. 30, 1953 | 600 |
| S-86 | 16-15-37-25W4 | 3049 | 623 | Chevron Sept. 14, 1953 | 571 |
| S-87 | 4-16-37-25W4 | 3122 | 721 | Chevron Sept. 13, 1953 | 650 |
| S-88 | 16-17-37-25W4 | 3194 | 813 | Chevron Dec. 23, 1951 | 727 |
| S-89 | 1-19-37-25W4 | 3250 | 879 | Chevron Oct. 10, 1953 | 830 |
| S-90 | 16-19-37-25W4 | 3190 | 827 | Chevron Dec. 9, 1951 | 767 |
| S-91 | 13-21-37-25W4 | 3171 | 732 | Royalite Oil May 28, 1952 | 701 |
| S-92 | 4-22-37-25W4 | 3099 | 743 | Chevron Sept. 8, 1953 | 631 |
| S-93 | 4-26-37-25W4 | 2985 | 547 | Royalite Oil May 27, 1952 | 491 |
| S-94 | 4-28-37-25W4 | 3146 | 916 | Chevron Sept 11, 1953 | 695 |
| S-95 | 4-29-37-25W4 | 3168 | 810 | Chevron Sept. 13, 1953 | 730 |
| S-96 | 4-30-37-25W4 | 3385 | 1010 | Royalite Oil June 3, 1952 | 955 |
| S-97 | 13-33-37-25W4 | 2876 | 492 | Royalite Oil May 22, 1952 | 469 |
| S-98 | 4-2-37-26W4 | 3116 | 831 | Chevron Sept. 7, 1951 | 786 |

| Elevation of L. Ardley 'B' (feet) | Thickness of L. Ardley 'B' (feet) | Thickness of Sandstone (feet) | Percent Sandstone | Depth to Bedrock (feet) |
|---|---|---|---|---|
| 2464 | 15 | 180 | 34 | 115 |
| 2467 | 15 | 206 | 36 | 137 |
| 2493 | 14 | 176 | 30 | |
| 2494 | 14 | 174 | 30 | |
| 2495 | 15 | 176 | 30 | |
| 2498 | 16 | 230 | 42 | 104 |
| 2478 | 15 | 182 | 35 | 117 |
| 2472 | 13 | 284 | 47 | 112 |
| 2467 | 15 | 248 | 37 | 85 |
| 2420 | 13 | 264 | 34 | 81 |
| 2423 | 15 | 240 | 34 | 111 |
| 2470 | 15 | 270 | 42 | 120 |
| 2468 | 15 | 170 | 29 | 166 |
| 2494 | 15 | 138 | 31 | 156 |
| 2451 | 14 | 312 | 48 | 132 |
| 2438 | 14 | 232 | 34 | 110 |
| 2430 | 15 | 286 | 32 | |
| 2407 | 15 | 178 | 43 | |
| 2330 | 22 | 284 | 39 | |

| Index Number | Location | Datum Elevation (feet) | Depth Logged (feet) | Company Date | Depth to top of L. Ardley 'B' (feet) |
|---|---|---|---|---|---|
| S-99 | 13-12-37-26W4 | 3235 | 924 | Chevron Dec. 13, 1951 | 883 |
| S-100 | 4-14-37-26W4 | 3178 | 1048 | Chevron Dec. 1, 1951 | 836 |
| S-101 | 13-23-37-26W4 | 3392 | 1092 | Chevron Dec. 18, 1951 | 1055 |
| S-102 | 13-24-37-26W4 | 3228 | 973 | Chevron Dec. 5, 1951 | 906 |
| S-103 | 13-24-37-26W4 | 3224 | 936 | Chevron Sept. 9, 1953 | 857 |
| S-104 | 1-1-38-26W4 | 2995 | 740 | Royalite Oil May 22, 1952 | 630 |
| C9-78 | 13-14-35-24W4 | 2875 | 790 | A.R.C. Aug. 8, 1978 | 282 |
| C4-74 | 12-22-35-25W4 | 3075 (G.L.) 3079 (K.B.) | 693 | A.R.C. June 12, 1974 | 628 |
| C11-74 | 2-28-36-26W4 | 3145 (G.L.) 3149 (K.B.) | 898 | A.R.C. June 19, 1974 | 779 |
| C12-74 | 15-22-36-25W4 | 3030 (G.L.) 3034 (K.B.) | 698 | A.R.C. June 21, 1974 | 558 |
| C13-74 | 16-16-36-24W4 | 3123 (G.L.) 3127 (K.B.) | 793 | A.R.C. June 18, 1974 | 565 |
| H-1 | 14-2-35-24W4 | 2858 (G.L.) 2870 (K.B.) | 7490 | Banff Oil 1954 | |
| H-2 | 10-8-35-24W4 | 3031 (G.L.) 3042 (K.B.) | 5700 | Kerr-McGee 1975 | |
| H-3 | 10-9-35-24W4 | 3077 (G.L.) 3089 (K.B.) | 5814 | Kerr-McGee 1976 | |
| H-4 | 7-10-35-24W4 | 2911 (G.L.) 2925 (K.B.) | 4916 | Camac Expl. | |
| H-5 | 6-19-35-24W4 | 3024 (G.L.) 3047 (K.B.) | 7803 | Phillips Pet. 1955 | |
| H-6 | 14-21-35-24W4 | 2890 (G.L.) 2902 (K.B.) | 7512 | Husky Oil 1955 | 347 |
| H-7 | 6-1-35-25W4 | 3072 (G.L.) 3085 (K.B.) | 8006 | B. A. Oil 1956 | 565 |
| H-10 | 10-14-35-25W4 | 3177 (G.L.) 3189 (K.B.) | 7065 | Zapata Pet. 1962 | |

| Elevation of L. Ardley 'B' (feet) | Thickness of L. Ardley 'B' (feet) | Thickness of Sandstone (feet) | Percent Sandstone | Depth to Bedrock (feet) |
|---|---|---|---|---|
| 2352 | 15 | 252 | 30 | |
| 2342 | 20 | 266 | 34 | 108 |
| 2337 | 16 | 370 | 37 | |
| 2322 | 14 | 228 | 27 | 84 |
| 2367 | 14 | 236 | 29 | 73 |
| 2365 | 15 | 168 | 29 | 56 |
| 2593 | 16 | 100 | 43 | 50 |
| 2451 | 20 | 236 | 41 | 25 |
| 2370 | 19 | 456 | 63 | 35 |
| 2476 | 19 | 170 | 34 | 45 |
| 2562 | 14 | 262 | 51 | 25 |
| 2555 | 17 | 110 | 39 | 115 |
| 2520 | 17 | | | |

| Index Number | Location | Datum Elevation (feet) | Depth Logged (feet) | Company Date | Depth to top of L. Ardley 'B' (feet) |
|---|---|---|---|---|---|
| H-11 | 13-14-35-24W4 | 3209 (K.B.) | 6295 | Husky Oil 1955 | 724 |
| H-12 | 6-17-35-25W4 | 3033 (G.L.) 3044 (K.B.) | 5813 | Amoco Oil 1970 | 610 |
| H-13 | 6-21-35-25W4 | 3098 (G.L.) 3112 (K.B.) | 3493 | Czar Resources 1977 | 642 |
| H-14 | 16-22-35-25W4 | 3150 (G.L.) 3162 (K.B.) | 7850 | Peyto Oil 1972 | |
| H-15 | 6-23-35-24W4 | 3160 (G.L.) 3173 (K.B.) | 7178 | Republic Resources 1974 | |
| H-16 | 4-27-35-25W4 | 3163 (K.B.) | 7998 | Federated Pet. 1953 | 698 |
| H-17 | 3-30-35-25W4 | 3043 (G.L.) 3057 (K.B.) | 8002 | Amurex Oil 1953 | 609 |
| H-18 | 6-33-35-25W4 | 3188 (G.L.) 3203 (K.B.) | 5957 | Can. Pacific Oil 1964 | 769 |
| H-19 | 6-34-35-25W4 | 3089 (G.L.) 3101 (K.B.) | 3247 | Phillips Pet. 1952 | 624 |
| H-20 | 1-35-35-25W4 | 3050 (G.L.) 3063 (K.B.) | 7067 | Seafort Pet. 1966 | |
| H-23 | 15-2-36-24W4 | 3068 (G.L.) 3081 (K.B.) | 7608 | Phillips Pet. 1955 | 482 |
| H-24 | 16-5-36-24W4 | 3015 (G.L.) 3027 (K.B.) | 6834 | Skelly Oil 1972 | |
| H-25 | 4-22-36-24W4 | 3133 (G.L.) 3146 (K.B.) | 5867 | Great Plains Dev. 1961 | |
| H-27 | 6-32-36-24W4 | 3088 (G.L.) 3100 (K.B.) | 5590 | Seafort Pet. 1966 | |
| H-28 | 11-5-36-25W4 | 3218 (G.L.) 3231 (K.B.) | 5998 | Gibraltar Oil 1972 | 800 |
| H-29 | 6-12-36-25W4 | 2966 (G.L.) 2979 (K.B.) | 7120 | Skelly Oil 1972 | |
| H-30 | 6-17-36-25W4 | 3253 (G.L.) 3265 (K.B.) | 6105 | Resman Holdings 1975 | 831 |
| H-31 | 6-18-36-25W4 | 3200 (G.L.) 3212 (K.B.) | 5366 | Resman Holdings 1975 | 780 |
| H-32 | 6-20-36-25W4 | 3223 (G.L.) 3236 (K.B.) | 5964 | Resman Holdings 1975 | 805 |

| Elevation of L. Ardley 'B' (feet) | Thickness of L. Ardley 'B' (feet) | Thickness of Sandstone (feet) | Percent Sandstone | Depth to Bedrock (feet) |
|---|---|---|---|---|
| 2485 | 20 | | | |
| 2434 | | | | |
| 2470 | 19 | | | |
| 2465 | 21 | | | |
| 2448 | 20 | | | |
| 2434 | 23 | | | |
| 2477 | 16 | | | |
| 2599 | 15 | 200 | 48 | |
| 2431 | 19 | | | |
| 2434 | 18 | | | |
| 2432 | 19 | | | |
| 2431 | 17 | | | |

| Index Number | Location | Datum Elevation (feet) | Depth Logged (feet) | Company Date | Depth to top of L. Ardley 'B' (feet) |
|---|---|---|---|---|---|
| H-33 | 6-26-36-25W4 | 3039 (G.L.)<br>3050 (K.B.) | 7075 | Imperial Oil<br>1959 | 560 |
| H-34 | 11-32-36-25W4 | 3092 (G.L.)<br>3105 (K.B.) | 7137 | Walnoco Oil<br>1973 | |
| H-35 | 7-11-36-26W4 | 3066 (G.L.)<br>3080 (K.B.) | 5885 | Amoco Petroleum<br>1972 | 665 |
| H-36 | 6-12-36-26W4 | 3030 (G.L.)<br>3044 (K.B.) | 5870 | Amoco Petroleum<br>1972 | |
| H-37 | 7-13-36-26W4 | 3084 (G.L.)<br>3097 (K.B.) | 5919 | Resman Holdings<br>1975 | 678 |
| H-38 | 6-14-36-26W4 | 3115 (G.L.)<br>3128 (K.B.) | 7710 | Diamond Shamrock<br>1970 | |
| H-39 | 2-23-36-26W4 | 3093 (G.L.)<br>3105 (K.B.) | 7522 | Shell Oil<br>1966 | |
| H-40 | 16-25-36-26W4 | 3167 (G.L.)<br>3180 (K.B.) | 7162 | Sohio Petroleum<br>1957 | 782 |
| H-41 | 7-36-36-26W4 | 3165 (G.L.)<br>3177 (K.B.) | 7188 | Merland Expl.<br>1974 | 786 |
| H-45 | 10-11-37-25W4 | 3069 (G.L.)<br>3085 (K.B.) | 7017 | Uno-Tex. Pet.<br>1962 | |
| H-46 | 16-16-37-25W4 | 3105 (G.L.)<br>3118 (K.B.) | 6871 | Central Del Rio<br>Oils - 1960 | |
| H-47 | 11-17-37-25W4 | 3194 (G.L.)<br>3208 (K.B.) | 7090 | B. A. Oil<br>1964 | 751 |
| H-48 | 11-23-37-25W4 | 3026 (G.L.)<br>3040 (K.B.) | 6701 | Union Texas<br>Natural Gas<br>1961 | |
| H-49 | 4-24-37-25W4 | 3002 (G.L.)<br>3016 (K.B.) | 6647 | Uno-Tex. Pet.<br>1963 | |
| H-52 | 1-27-37-25W4 | 2945 (G.L.)<br>2957 (K.B.) | 6671 | Union Texas<br>Natural Gas<br>1961 | |
| H-53 | 11-14-37-26W4 | 3214 (G.L.)<br>3228 (K.B.) | 7356 | Sun Oil<br>1969 | 878 |
| H-54 | 10-22-37-26W4 | 3145 (G.L.)<br>3157 (K.B.) | 6153 | Amerada Pet.<br>1964 | 812 |

| Elevation of L. Ardley 'B' (feet) | Thickness of L. Ardley 'B' (feet) | Thickness of Sandstone (feet) | Percent Sandstone | Depth to Bedrock (feet) |
|---|---|---|---|---|
| 2490 | 15 | 150 | 30 | |
| 2415 | 19 | | | |
| 2419 | 20 | | | |
| 2398 | 17 | | | |
| 2391 | 17 | | | |
| 2457 | 16 | | | |
| 2350 | 22 | | | |
| 2345 | 20 | | | |

## **APPENDIX D:** Selected Aquifer Test Analyses

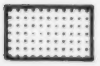
SYMBOLS USED IN GEOLOGIC STRIP LOGS

Till

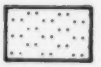
Clay

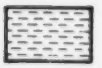
Silty Clay

Sand

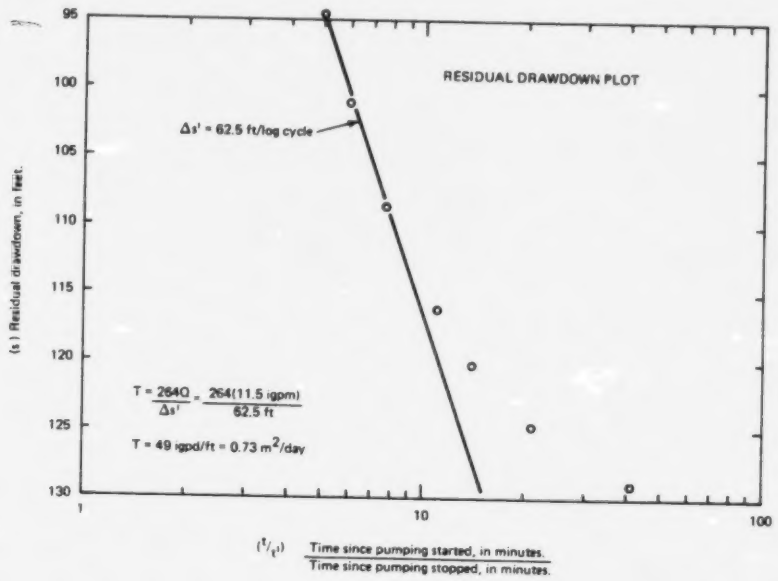

Sandstone

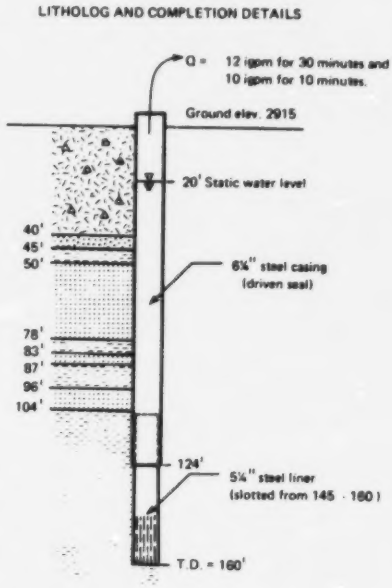
Sandstone, bentonitic


Siltstone

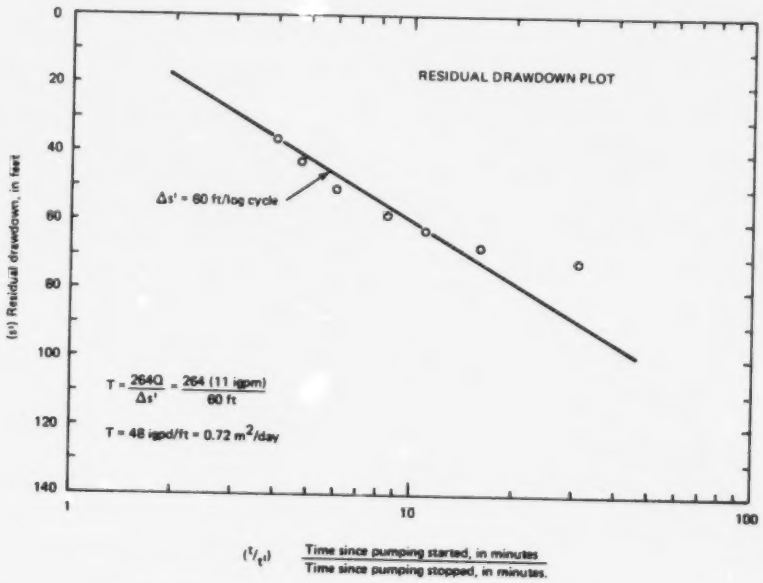

Shale

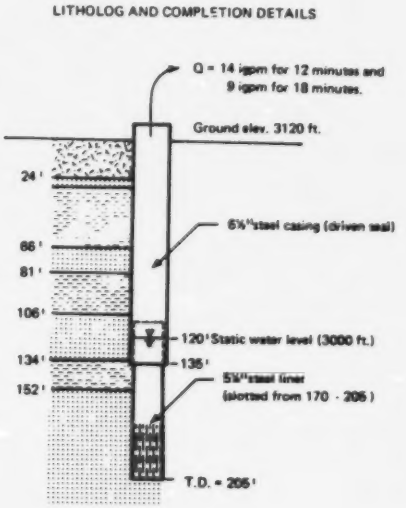
Coal



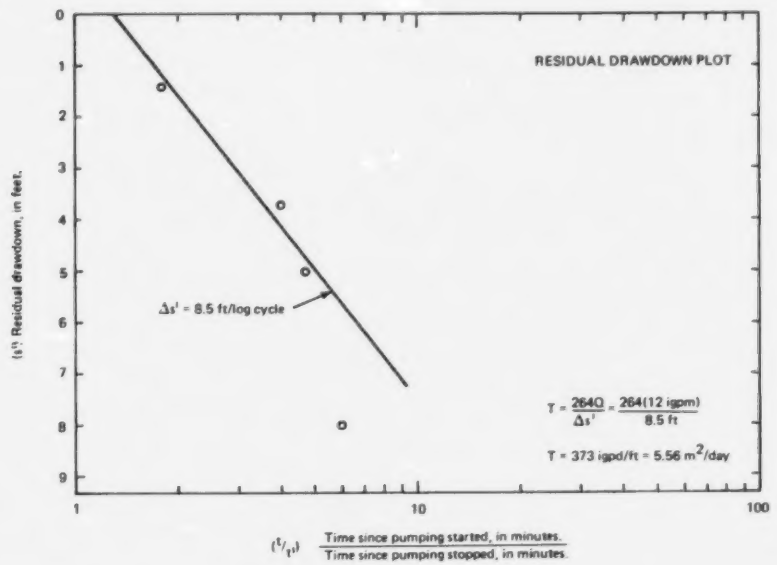



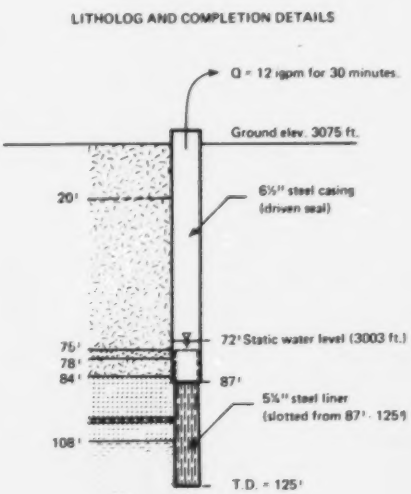

## Well No. 33.5: 11-28-35-24W4



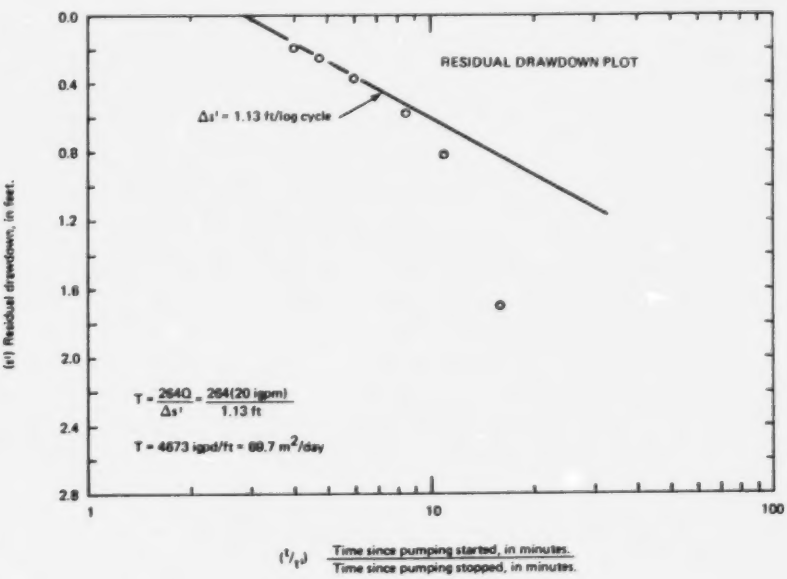



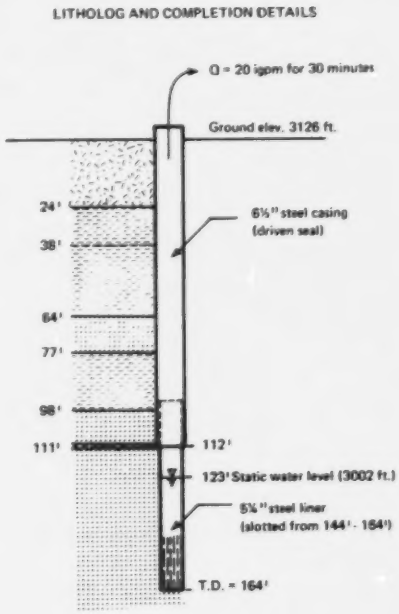

## Well No. 57: 13-13-35-25W4


RESIDUAL DRAWDOWN PLOT
(s') Residual drawdown, in feet.
Δs' = 8.5 ft/log cycle
T = 264Q/Δs' = 264(12 igpm)/8.5 ft
T = 373 igpd/ft = 5.56 m²/day
(t/t') Time since pumping started, in minutes. / Time since pumping stopped, in minutes.

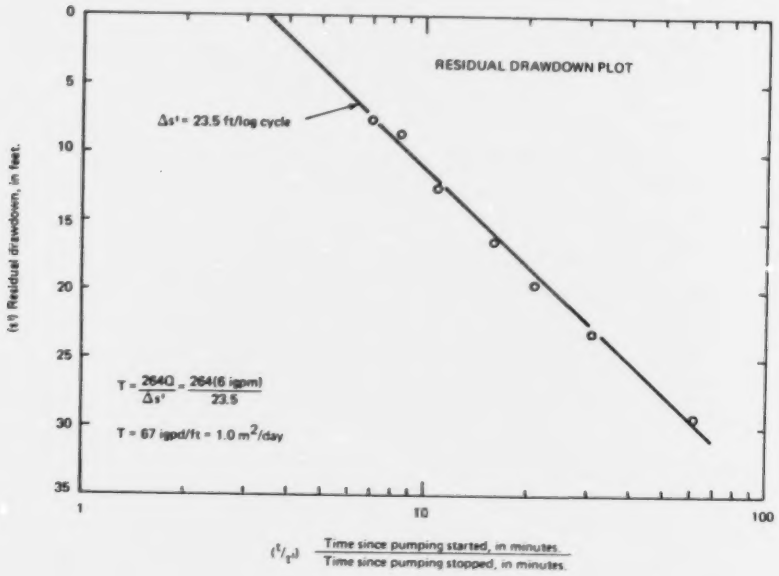


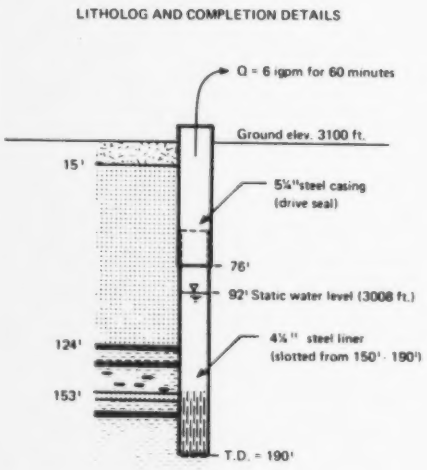

## Well No. 61: 1-17-35-25W4


RESIDUAL DRAWDOWN PLOT
(s') Residual drawdown, in feet.
Δs' = 1.13 ft/log cycle
T = 264Q/Δs' = 264(20 igpm)/1.13 ft
T = 4673 igpd/ft = 69.7 m²/day
(t/t') Time since pumping started, in minutes. / Time since pumping stopped, in minutes.

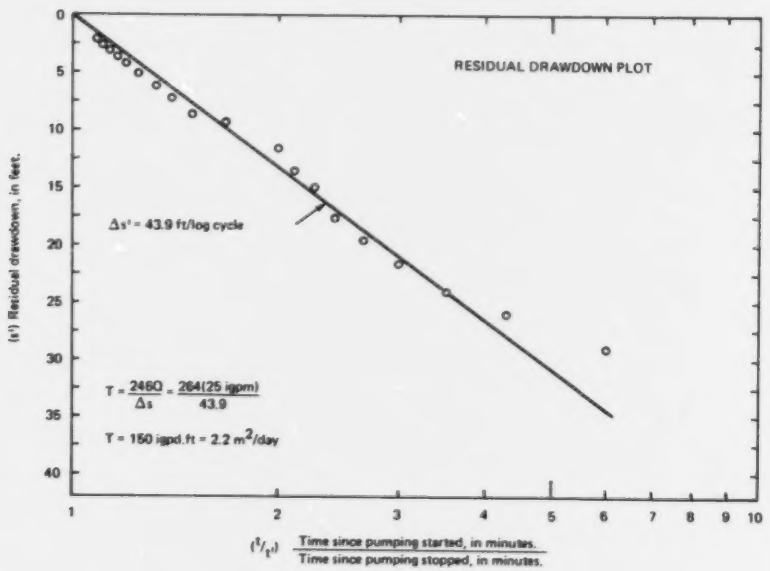


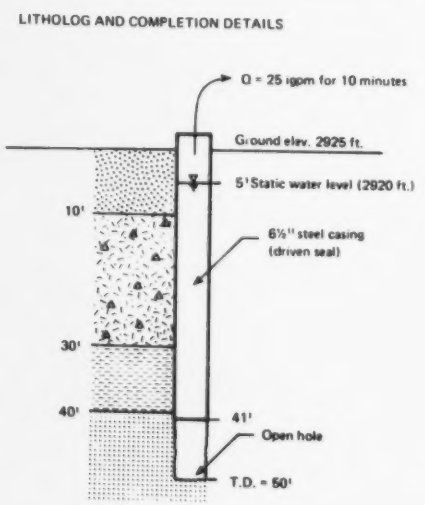

## Well No. 71: 9-27-35-25W4


RESIDUAL DRAWDOWN PLOT
Δs' = 23.5 ft/log cycle
T = 264Q/Δs' = 264(6 igpm)/23.5
T = 67 igpd/ft = 1.0 m²/day
(s') Residual drawdown, in feet.
(t/t') Time since pumping started, in minutes / Time since pumping stopped, in minutes.

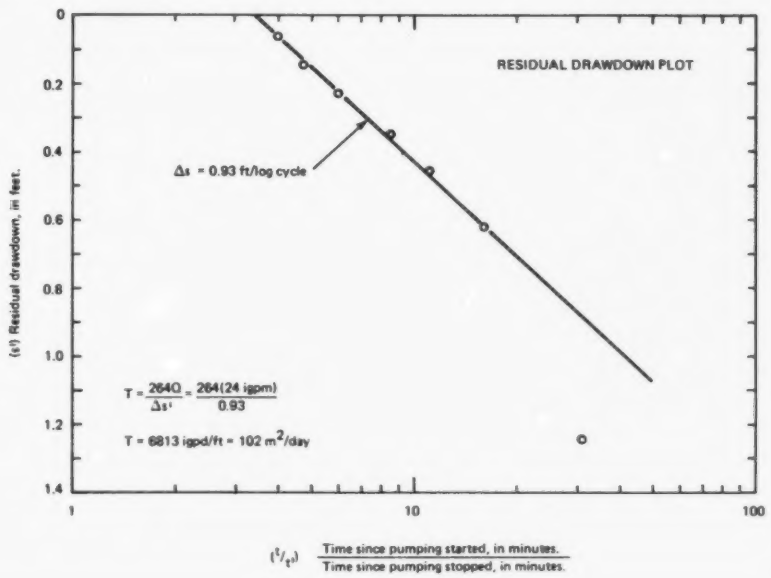


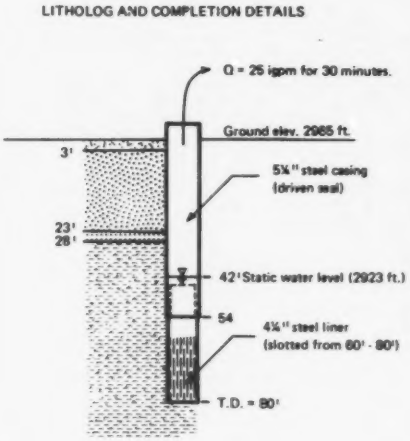

## Well No. 83: 13-2-36-24W4


RESIDUAL DRAWDOWN PLOT
Δs' = 43.9 ft/log cycle
T = 246Q/Δs = 264(25 igpm)/43.9
T = 150 igpd.ft = 2.2 m²/day
(s') Residual drawdown, in feet.
(t/t') Time since pumping started, in minutes / Time since pumping stopped, in minutes.

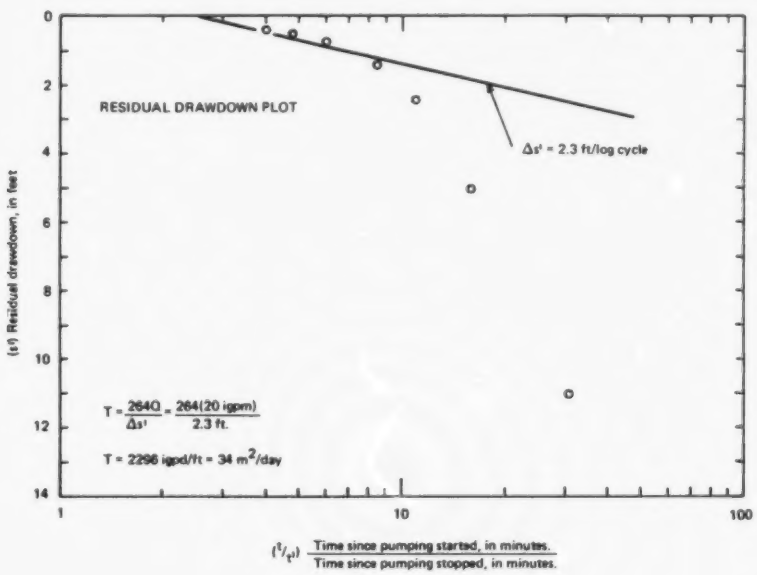


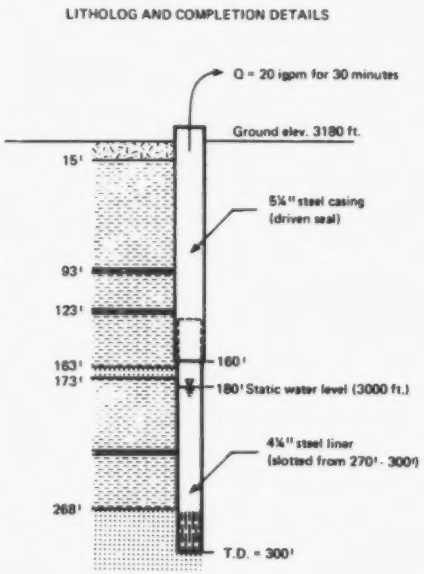

## Well No. 96: 16-6-36-24W4



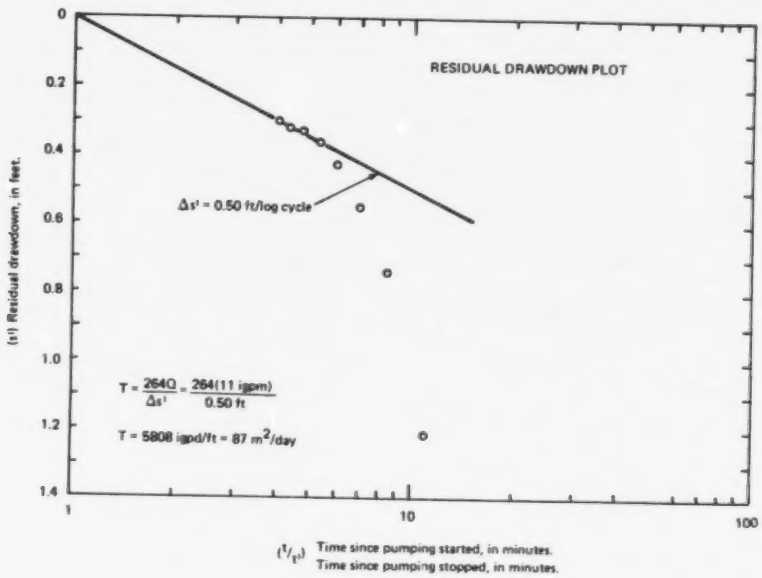



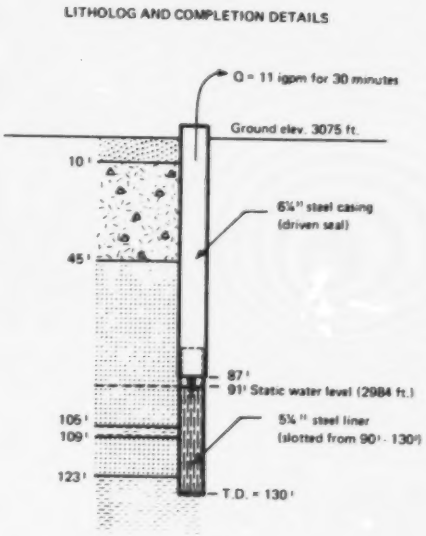

## Well No. 110: 4-18-36-24W4



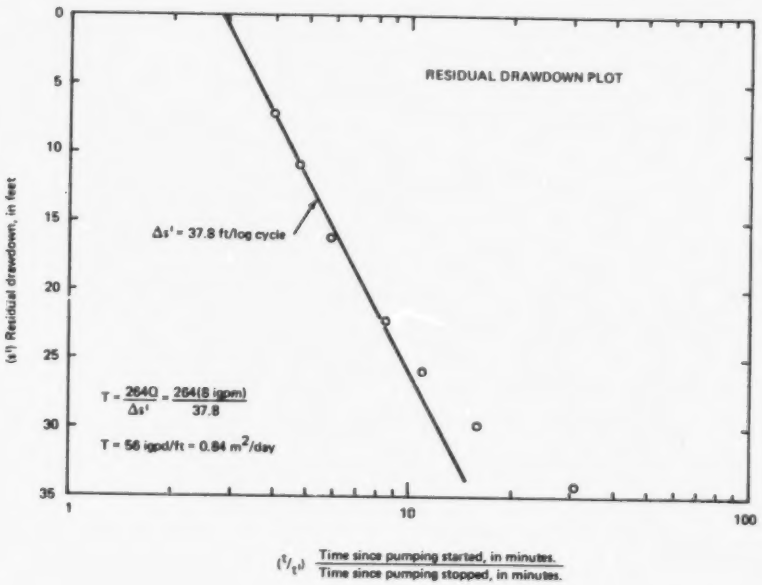



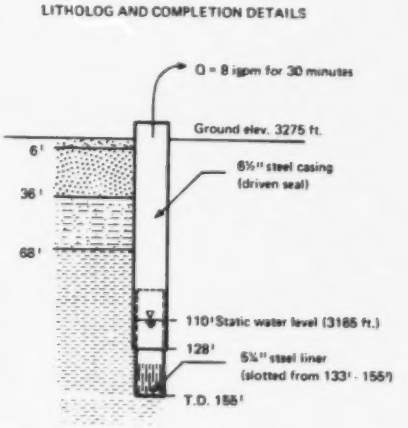

## Well No. 138: 2-28-36-24W4


RESIDUAL DRAWDOWN PLOT
(s') Residual drawdown, in feet
Δs' = 0.50 ft/log cycle
T = 264Q/Δs' = 264(11 igpm)/0.50 ft
T = 5808 igpd/ft = 87 m²/day
(t/t') Time since pumping started, in minutes. / Time since pumping stopped, in minutes.

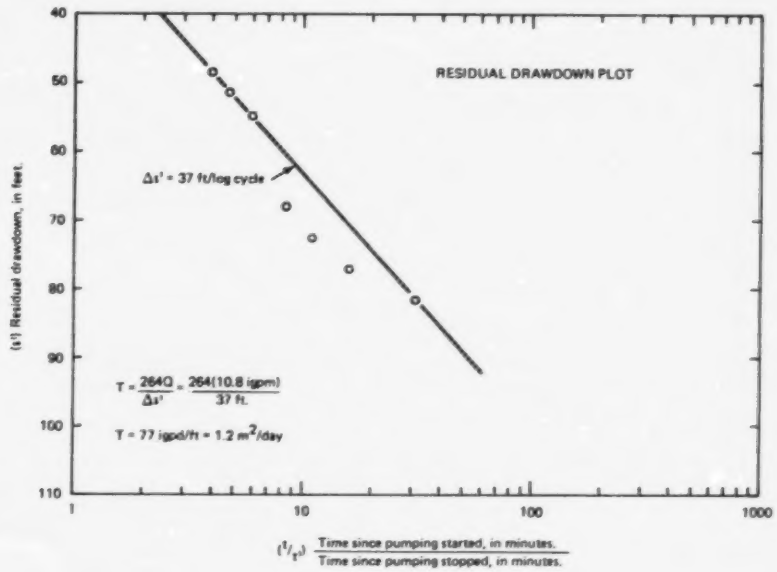


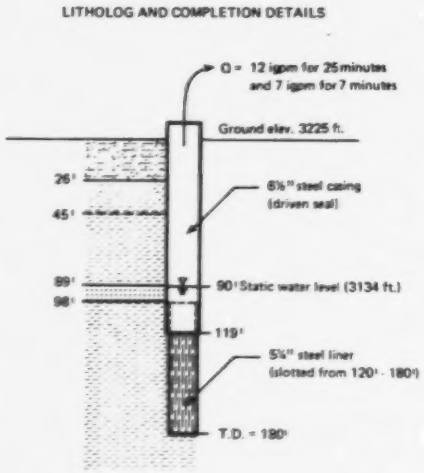

## Well No. 151: 12-33-36-24W4


RESIDUAL DRAWDOWN PLOT
(s') Residual drawdown, in feet
Δs' = 37.8 ft/log cycle
T = 264Q/Δs' = 264(8 igpm)/37.8
T = 56 igpd/ft = 0.84 m²/day
(t/t') Time since pumping started, in minutes. / Time since pumping stopped, in minutes.

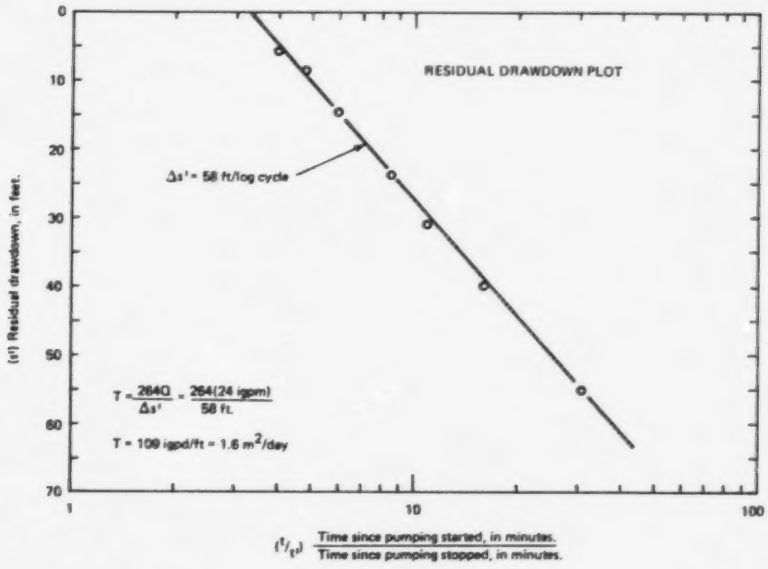


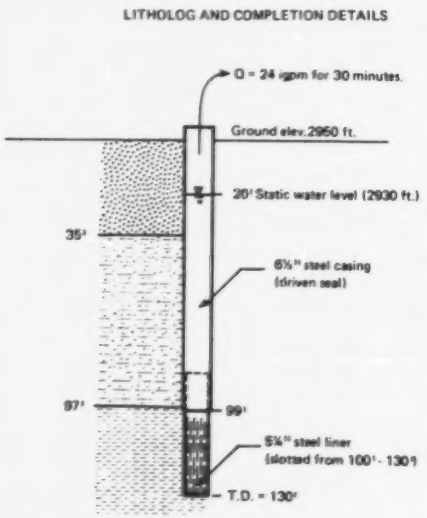

## Well No. 162: 16-8-36-25W4



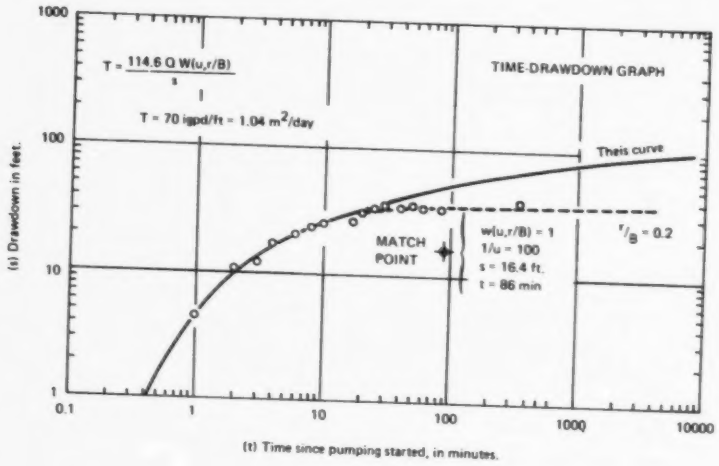


LITHOLOG AND COMPLETION DETAILS
Q = 12 igpm for 25 minutes and 7 igpm for 7 minutes
Ground elev. 3225 ft.
26'
45'
6⅝" steel casing (driven seal)
89'
90' Static water level (3134 ft.)
98'
119'
5¼" steel liner (slotted from 120' - 180')
T.D. = 180'

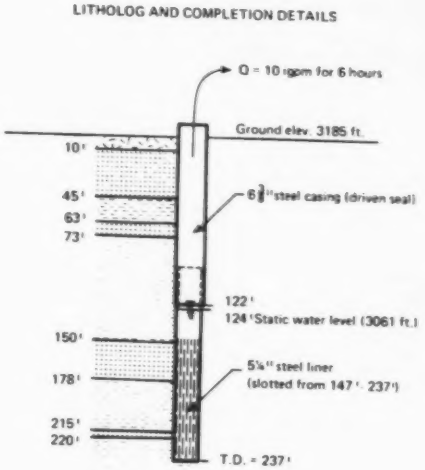
## Well No. 165: 5-9-36-25W4



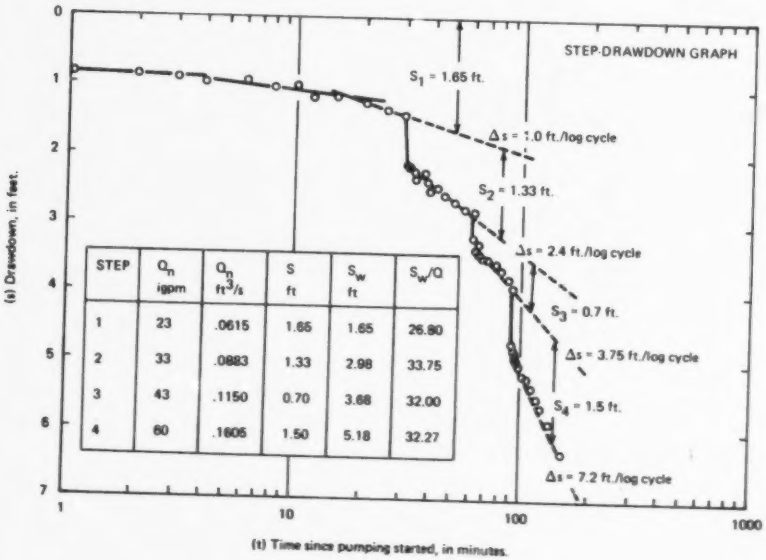


LITHOLOG AND COMPLETION DETAILS
Q = 24 igpm for 30 minutes.
Ground elev. 2950 ft.
20' Static water level (2930 ft.)
35'
6⅝" steel casing (driven seal)
97'
99'
5¼" steel liner (slotted from 100' - 130')
T.D. = 130'

## Well No. 317: 6-24-37-25W4

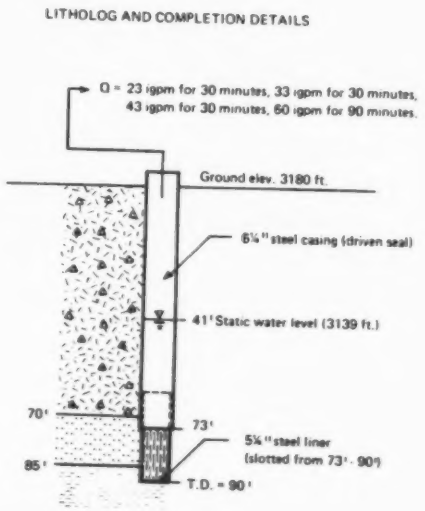


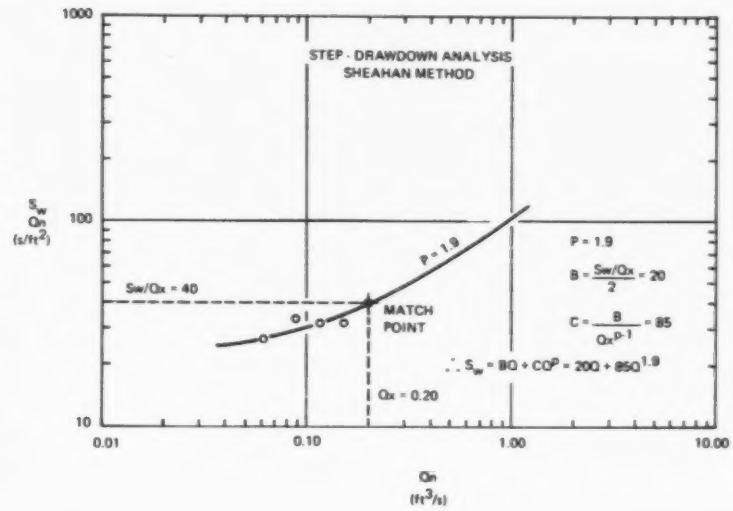

## Well No. 330: 16-4-37-26W4

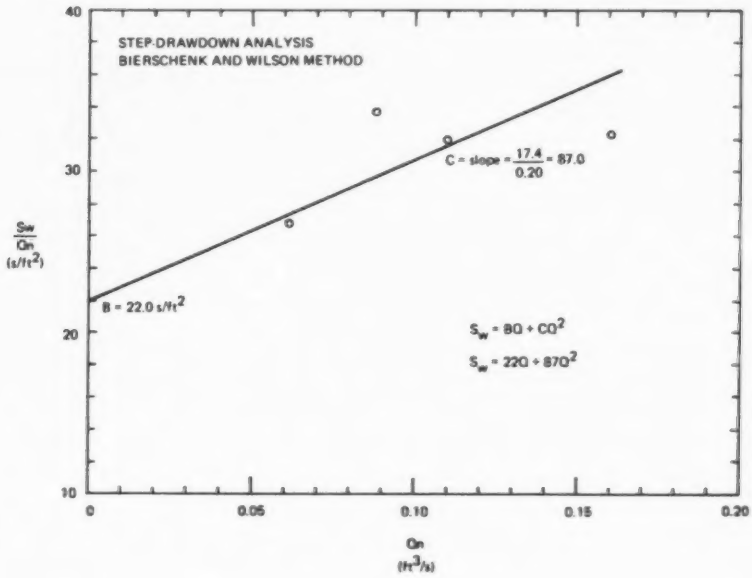



| STEP | $Q_n$ igpm | $Q_n$ $ft^3/s$ | S ft | $S_w$ ft | $S_w/Q$ |
|---|---|---|---|---|---|
| 1 | 23 | .0615 | 1.65 | 1.65 | 26.80 |
| 2 | 33 | .0883 | 1.33 | 2.98 | 33.75 |
| 3 | 43 | .1150 | 0.70 | 3.68 | 32.00 |
| 4 | 60 | .1605 | 1.50 | 5.18 | 32.27 |

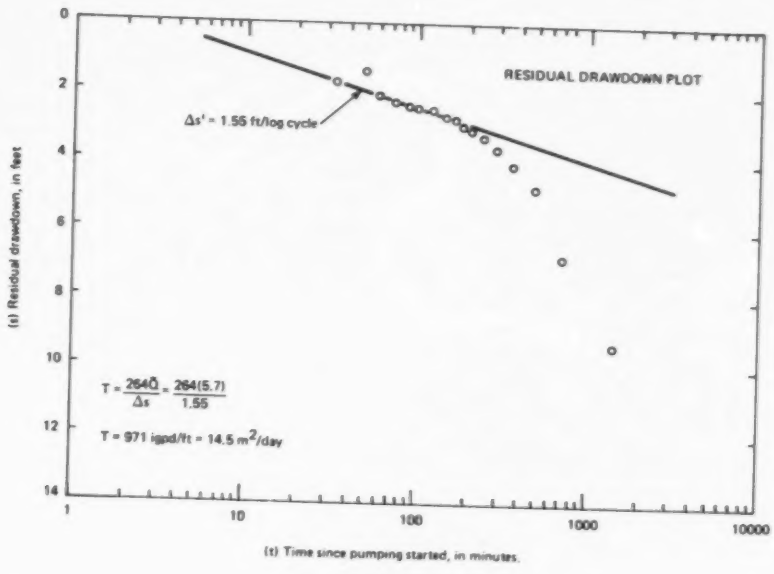

LITHOLOG AND COMPLETION DETAILS
Q = 23 igpm for 30 minutes, 33 igpm for 30 minutes,
43 igpm for 30 minutes, 60 igpm for 90 minutes.
Ground elev. 3180 ft.
6¼" steel casing (driven seal)
41' Static water level (3139 ft.)
70'
73'
5¼" steel liner
(slotted from 73' - 90')
85'
T.D. = 90'

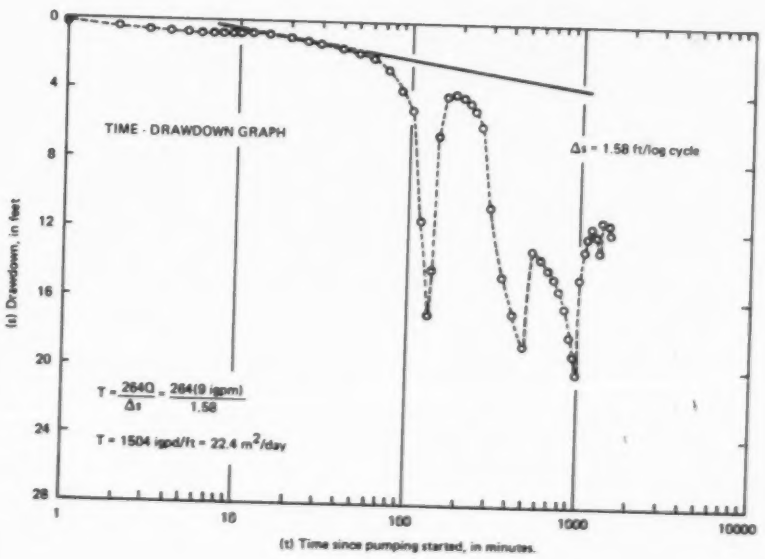
## Well No. 335.5: 16-10-37-26W4

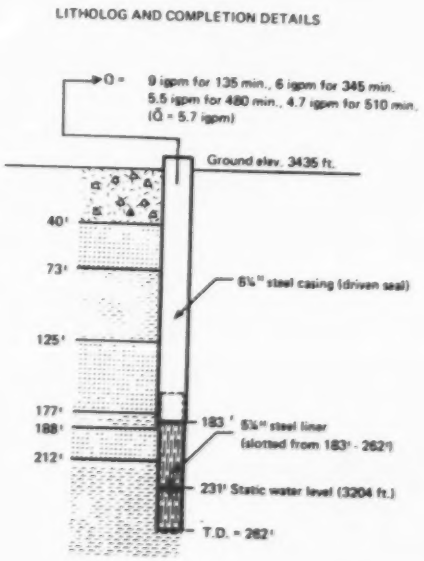



**Well No. 335.5: 16-10-37-26W4**


RESIDUAL DRAWDOWN PLOT
Δs' = 1.55 ft/log cycle
(s) Residual drawdown, in feet
T = 264Q/Δs = 264(5.7)/1.55
T = 971 igpd/ft = 14.5 m²/day
(t) Time since pumping started, in minutes.


TIME - DRAWDOWN GRAPH
Δs = 1.58 ft/log cycle
(s) Drawdown, in feet
T = 264Q/Δs = 264(9 igpm)/1.58
T = 1504 igpd/ft = 22.4 m²/day
(t) Time since pumping started, in minutes.




**Well No. 343: 1-23-37-26W4**

MAPS NOT

FILMED

CARTES

OMISES